echnical Memorandum NESS 59

# USE OF GEOSTATIONARY-SATELLITE CLOUD VECTORS TO ESTIMATE TROPICAL CYCLONE INTENSITY

Carl O. Erickson

Meteorological Satellite Laboratory
Washington, D.C.
September 1974

noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / National Environmental Satellite Service

NOAA TECHNICAL MEMORANDUMS

National Environmental Satellite Service Series

The National Environmental Satellite Service (NESS) is responsible for the establishment and operation of the environmental satellite systems of NOAA.

NOAA Technical Memorandums facilitate rapid distribution of material that may be preliminary in nature and so may be published formally elsewhere at a later date. Publications 1 through 20 and 22 through 25 are in the earlier ESSA National Environmental Satellite Center Technical Memorandum (NESCTM) series. The current NOAA Technical Memorandum NESS series includes 21, 26, and subsequent issuances.

Publications listed below are available from the National Technical Information Service, U.S. Department of Commerce, Sills Bldg., 5285 Port Royal Road, Springfield, Va. 22151. Price: $3.00 paper copy; $1.45 microfiche. Order by accession number (given in parentheses). Information on memorandums not listed below can be obtained from D811, Environmental Data Service, 3300 Whitehaven St., NW, Washington, D.C. 20235.

ESSA Technical Memorandums

NESCTM 22 Publications and Final Reports on Contracts and Grants, 1969--NESC. January 1970. (PB-190-632)

NESCTM 23 Estimating Mean Relative Humidity From the Surface to 500 Millibars by Use of Satellite Pictures. Frank J. Smigielski and Lee M. Mace, March 1970. (PB-191-741)

NESCTM 24 Operational Brightness Normalization of ATS-1 Cloud Pictures. V. R. Taylor, August 1970. (PB-194-638)

NESCTM 25 Aircraft Microwave Measurements of the Arctic Ice Pack. Alan E. Strong and Michael H. Fleming, August 1970. (PB-194-588)

NOAA Technical Memorandums

NESS 21 Geostationary Satellite Position and Attitude Determination Using Picture Landmarks. William J. Dambeck, August 1972. (COM-72-10916)

NESS 26 Potential of Satellite Microwave Sensing for Hydrology and Oceanography Measurements. John C. Alishouse, Donald R. Baker, E. Paul McClain, and Harold W. Yates, March 1971. (COM-71-00544)

NESS 27 A Review of Passive Microwave Remote Sensing. James J. Whalen, March 1971. (COM-72-10546)

NESS 28 Calculation of Clear-Column Radiances Using Airborne Infrared Temperature Profile Radiometer Measurements Over Partly Cloudy Areas. William L. Smith, March 1971. (COM-71-00556)

NESS 29 The Operational Processing of Solar Proton Monitor and Flat Plate Radiometer Data. Henry L. Phillips and Louis Rubin, May 1972. (COM-72-10719)

NESS 30 Limits on the Accuracy of Infrared Radiation Measurements of Sea-Surface Temperature From a Satellite. Charles Braun, December 1971. (COM-72-10898)

NESS 31 Publications and Final Reports on Contracts and Grants, 1970--NESS. December 1971. (COM-72-10303)

NESS 32 On Reference Levels for Determining Height Profiles From Satellite-Measured Temperature Profiles. Christopher M. Hayden, December 1971. (COM-72-50393)

NESS 33 Use of Satellite Data in East Coast Snowstorm Forecasting. Frances C. Parmenter, February 1972. (COM-72-10482)

NESS 34 Chromium Dioxide Recording--Its Characteristics and Potential for Telemetry. Florence Nesh, March 1972. (COM-72-10644)

NESS 35 Modified Version of the Improved TIROS Operational Satellite (ITOS D-G). A. Schwalb, April 1972. (COM-72-10547)

(Continued on inside back cover)

NOAA Technical Memorandum NESS 59

# USE OF GEOSTATIONARY-SATELLITE CLOUD VECTORS TO ESTIMATE TROPICAL CYCLONE INTENSITY

Carl O. Erickson

Meteorological Satellite Laboratory
Washington, D.C.
September 1974



UNITED STATES
DEPARTMENT OF COMMERCE
Frederick B. Dent, Secretary

NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION
Robert M. White, Administrator

National Environmental
Satellite Service
David S. Johnson, Director

CONTENTS

LIST OF FIGURES

# USE OF GEOSTATIONARY-SATELLITE CLOUD VECTORS TO ESTIMATE TROPICAL CYCLONE INTENSITY

Carl O. Erickson
Meteorological Satellite Laboratory, NESS
Washington, D. C.

ABSTRACT. Polynomial-fitting techniques are applied to the fields of high-cloud vectors over tropical cyclones to yield numerical calculations of divergence, vorticity, and other parameters. The correlation between maximum low-level wind speed and the parameter mean divergence/vertical shear is approximately +0.6. This relationship is statistically significant and believed to be potentially useful. Other parameters and combinations relate less well to storm intensity and to change in intensity.

For good results from the polynomial-fitting technique, it is important to obtain 12 or more vectors distributed over at least 3 quadrants of the storm. That is not always possible.

Some qualitative findings relating cyclone intensity to certain cloud configurations or flow patterns are presented. Those findings can be helpful in specialized cases.

## I. INTRODUCTION

Techniques for estimating wind speeds in tropical cyclones from satellite pictures of the cloud patterns of those cyclones have now been in use for a number of years. Fett (1964) and Fritz et al. (1966) pioneered in the interpretation of single photographs. More recently, Dvorak (1973) developed an improved system using photographs of the same storm on two or more consecutive days. The better quality and more nearly vertical view of present-day satellite photographs also has contributed to improved performance.

The geostationary Applications Technology Satellites, ATS 1 (launched December 1966) and ATS 3 (launched November 1967), have produced daily multiple earth images at approximate 25-min intervals on many days. Selected ATS photographs, of course, can and have been used in the Dvorak technique. However, animated cloud picture sequences (movies) also have been produced, and fields of cloud vectors, representing displacements over periods ranging from one to several hours, can be derived from these film transparencies. This report concerns the attempt to use such cloud vector data as a diagnostic tool in dealing with tropical cyclones. Certainly, this tool will not supplant existing techniques for estimating tropical storm intensity; but the results of this study indicate that for certain cases the analysis of cloud vectors can be a valuable addition to those techniques.

## 2. DATA LIMITATIONS AND PROSPECTS

### General Limitations

Hubert and Whitney (1971) list five sources of error in wind estimates from geostationary-satellite pictures. These are:

- Uncertainty of target cloud height,
- nonadvective cloud motion,
- errors of measurement,
- errors in tracking cloud targets, and
- errors attributable to nonrepresentative rawinsonde observation. (This does not affect the accuracy of wind estimates, but it does contribute to deviations between rawinsonde observations and cloud vectors).

The reader is referred to the Hubert and Whitney paper for a more complete discussion.

To some extent, all of the above errors must have entered into the calculations of the present study; hopefully, such errors were relatively small. In addition, there are problems peculiar to the thick cloud masses accompanying tropical cyclone situations. These problems are discussed in succeeding paragraphs. A capsule summation might read, "Vectors are where one finds them, rather than where one might wish them to be!"

### Limitations in Tropical Cyclones

In attempting to determine cloud displacements and other short-term changes in cloud configuration in and around tropical cyclones, it soon becomes obvious that high-cloud vectors are much more easily obtainable than low-cloud vectors. This, of course, is because the cirrus canopy generated by tropical cyclones and disturbances usually obscures the lower clouds. (The resultant climatological bias in cloud vectors over disturbed areas has been discussed by Gruber et al., 1971). It is possible, however, to employ visual enhancement techniques to reveal the motions of lower level dense convective elements within storms and disturbed areas. But Bradbury (1971), in a study of the radar echo motions about hurricane Camille, concluded that, "If enhanced ATS cloud pictures are to be used...., the time interval between pictures will have to be on the order of 5 to 7 min as a maximum." The requirement for such a short interval precludes the use of nearly all existing ATS data for determining low or middle-level winds near storm centers through enhancement techniques.

Still another unfavorable condition in tropical cyclones is that the dense featureless canopy often seen over the interior of well-developed storms usually precludes obtaining reliable vectors at any cloud level near the storm center. For weaker storms and disturbances, a few cirrus vectors near the center sometimes can be determined. However, the vast bulk of the cirrus vectors of this study were, of necessity, measured over the middle and outer reaches of the canopy -- i.e., nearly always at radii of more than 2° of latitude from the storm center.

Therefore, although low-cloud vectors can and sometimes do contribute useful information about tropical cyclones, and although high or low-level vectors near the center also may occasionally contribute useful data, these sources must be regarded as fortuitous and unreliable. Consequently, this report deals largely with results from high-cloud vectors located primarily over the middle and outer reaches of the disturbance and frequently distributed quite unequally through various quadrants.

An additional restriction was that tropical cyclones observed by ATS 1 in the Eastern Pacific generally are not as well documented as are those observed by ATS 3 in the North Atlantic and Caribbean area. Also, ATS 1 photographic capability was lost in October 1972. Therefore, only vectors derived from the ATS 3 satellite pictures have been used in this study. These upper tropospheric cloud vectors derived from satellite pictures were supplemented where appropriate with 200-mb rawinsonde data.

## Evidence of Favorable Prospects

At this point, it is well to reiterate that, despite the limitations on the use of cloud vector data in tropical cyclones, pre-existing evidence indicates that high-cloud motions should provide valuable clues about storm intensity. Fritz et al. (1966) and Hubert and Timchalk (1969) have presented observational evidence of a positive correlation between canopy size and maximum wind speed. Numerical calculations by Estoque (1971) have related the intensity of the upper level outflow to the size of the cirrus canopy. Thus, the relationship between canopy size and storm intensity is supported by both observation and theory. It is reasonable to suppose that the magnitude of the upper level horizontal divergence should also bear a positive relationship to storm intensity. The divergence (and other derived parameters) can be calculated from a field of cloud vectors, subject to the vector limitations already noted.

On the larger scale synoptic picture, North Atlantic tropical cyclone development is known to be favored by certain circulation patterns (Dunn and Miller 1961; Riehl 1954; Merritt 1967). To the extent that cloud vector data can reveal these circulation patterns, such data are a helpful diagnostic tool.

With respect to the influence of the vertical structure of the atmosphere upon tropical storm development, the importance of small values of vertical wind shear through a deep layer of the troposphere has been pointed out by Riehl (1954) and re-emphasized by Gray (1968, 1970). Again, to the extent that cloud vectors permit inferences about the vertical shear, such vectors should be useful.

# 3. PROCEDURE

## Approach

The basic approach of this study was to try to relate quantitatively certain calculated parameters (derived from the field of high-cloud vectors over the storm) to the observed or estimated storm intensity and change in intensity. A numerical program, using the high-level[1] vector data as input. was used to generate grid-point fields of divergence, vorticity, total wind, and u v components. The program employs polynomial-fitting techniques adapted from the work of Schmidt and Johnson (1972); the technique is described in appendix A. For the center of the storm or disturbance, point values of the field quantities also were obtained. Other derived parameters were vertical shear, mean horizontal divergence, and mean outflow. Correlation coefficients between these various parameters and storm intensity and intensity change were calculated.

A secondary approach was to note any unusual or distinctive cloud configuration or upper level flow pattern that may have been related to storm intensity or change in intensity. Results here are qualitative and restricted, but appear useful for certain cases.

Storm data (position, movement, intensity, change in intensity) were obtained from various published sources (Simpson and Hebert 1973; Simpson and Hope 1972; Sugg and Hebert 1969; Simpson and Pelissier 1971; Simpson et al. 1970) and reconnaissance reports, or were estimated from synoptic analyses.

## Sources of Vectors

ATS 3 cloud vectors used in this study came from several sources; some rawinsonde data also were used. The five basic source categories are:

(1) NESS film loops,
(2) Film loops obtained from T. T. Fujita,
(3) The Electronic Animation System (E.A.S) in the Meteorological Satellite Laboratory, NESS,
(4) Vector sets derived by other researchers (Timchalk, NESS unpublished; Smith 1972; Fujita and Black 1970, and
(5) Rawinsonde data (200 mb or 150 mb).[2]

---

[1]These data are assumed to be at or higher than the 300-mb level.

[2]Hubert and Whitney (1971) give 30,000 ft as the statistical "level of best fit" for cirrus vectors vs. rawinsonde data. Because the cirrus vectors of the present study were measured in the vicinity of tropical storms and disturbances, where the troposphere is of greater depth than in middle latitudes, it is believed that 200 mb is a more appropriate level. In the case of the very intense hurricane Camille of 1969, the 150-mb rawinsonde data were used.

Vectors from sources (1) and (2) were obtained following the general procedures described by Young et al. (1972). The chief difference between this and operational practice was that a concentrated effort was made to obtain a good distribution of vectors over and around the particular cloudy area of interest. Other photographed areas were ignored.

## Selection of Cases

In selecting cases of tropical cyclones and disturbances for which high-level vector data might be obtained, the initial efforts were somewhat experimental. Cloud vectors for likely cases were obtained by using the Electronic Animation System (E.A.S.) or from previously prepared movie loops following operational procedures (Young et al. 1972). Some vector sets eventually were judged to be insufficient because of poor registration, poor picture quality, poor vector distribution, or gross uncertainty about the cloud height.

Later during the selection process, some sets of high-level vectors were obtained from other sources, and some earlier sets that had initially been rejected because of poor areal distribution were made acceptable by the addition of 200-mb rawinsonde data.

Some storms and disturbances were observed on two or three movie loops, representing two or three different time periods during a day. Vector sets were derived for each of these periods; if the sets were acceptable, they were counted as separate cases.

The selection criteria that evolved are:

- Storm or disturbance must be centered over water;
- high-level vectors must be distributed so that the storm center is embedded within the data perimeter by at least one-half degree of latitude;
- pictures or film loops from which vectors are derived must not be of obviously poor quality or poor registration;
- there must be at least four vectors (the vast majority of cases had 10 to 25 vectors); and
- the tropical storm or disturbance need not have been a named storm (although many were, or later became so). However, it must appear on satellite photographs as a recognizable cloud cluster or area of enhanced convective cloudiness in the tropics or subtropics.

For a case to survive and to enter into the results, all of the above criteria had to exist simultaneously. It should be noted that these criteria are not particularly stringent. Many cases should qualify under operational conditions. Examples of good, marginally acceptable, and non-acceptable fields of vectors are illustrated in figure 1. Well over 100 possible cases over the North Atlantic - Caribbean region[3] for the 6-yr

[3] One eastern Pacific storm, hurricane Ava of 1973, is included.

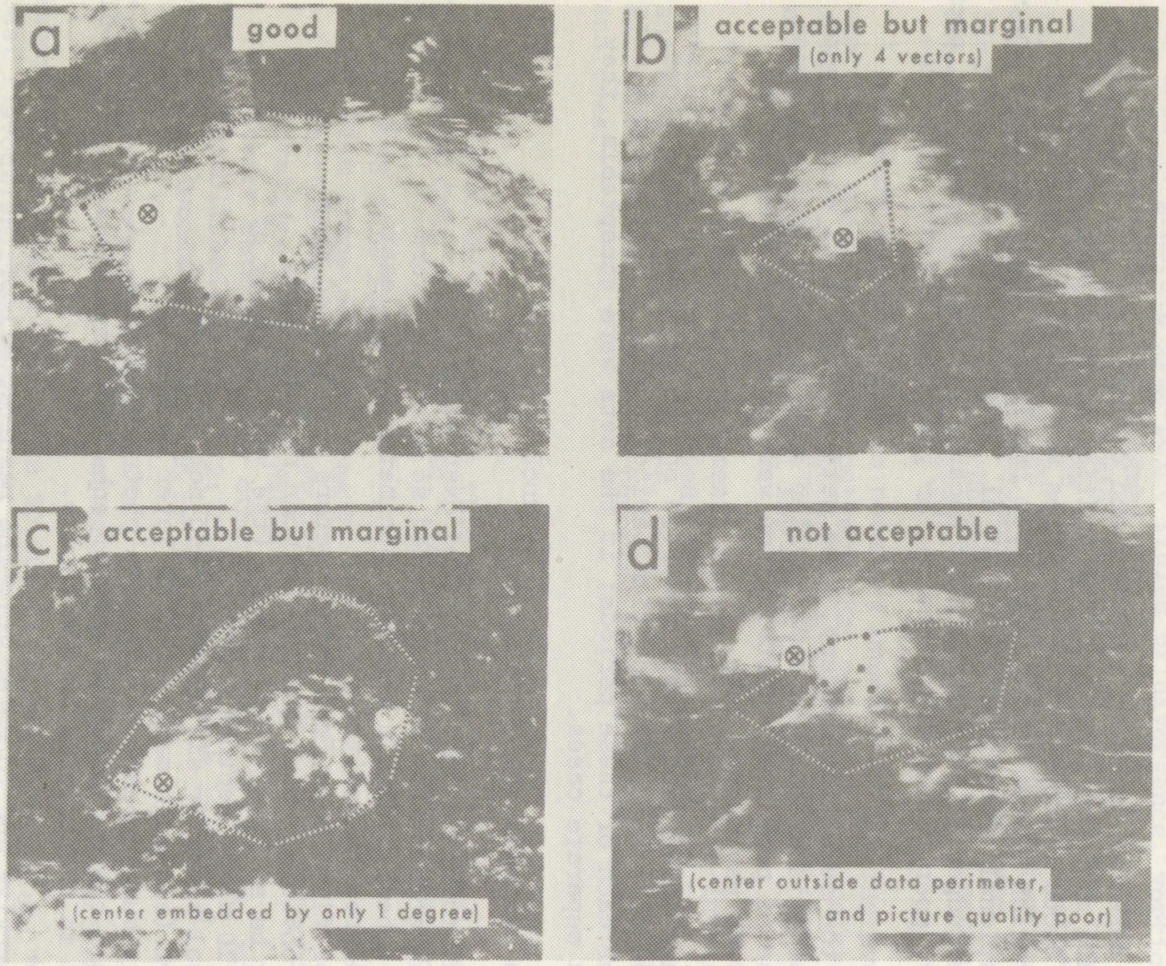


Figure 1.--Examples of good, marginally acceptable, and unacceptable fields of vectors. Black dots are vector locations, dotted lines indicate perimeters of the data, and the symbols ⊗ denote locations of disturbance centers. (a) Agnes, June 16, 1972; (b) Alma, May 23, 1970; (c) pre-Brenda, Aug. 15, 1973; (d) Alma, May 24, 1970. (The poor picture quality of (b) is not a factor in that particular case because rawinsonde data are used.)

period, 1968 through 1973, were initially considered. Eighty-eight of those met the five criteria above. Documentation for those 88 cases is given in table 5, appendix B.

The very small minimum number of vectors used deserves explanation. Most cases had many more than the four required as a minimum. However, as the study progressed, and as rawinsonde data were used to augment some vector fields, it seemed appropriate to find out if useful results could be obtained for some Caribbean disturbances where only rawinsonde data were available. The few cases having four vectors were all of this type. And most other vector fields having a count of 10 or fewer vectors (a minority of the 88 cases) were entirely, or partly, derived from rawinsonde data.

The vector sets derived exclusively from rawinsonde data yielded erratic results. The large spacing of the rawinsonde network in the Caribbean - Gulf of Mexico region (when introduced into the numerical program used in this study) apparently is not adequate to define the fields of divergence and other parameters with sufficient realism. Hurricane Camille, 1969, was a particular disappointment. Rawinsonde data were used exclusively on several days of that very intense storm, and the results were poor. (Some constraints within the numerical program. discussed later, may well have contributed to the poor results). One conclusion of this study is that, while rawinsonde data may be very helpful for augmenting a field of satellite-derived cloud vectors, the rawinsonde data by themselves are insufficient to provide reliable estimates of divergence and other wind-derived parameters over tropical cyclones. That conclusion is hardly surprising.

Because of the poor results from some of the 88 "acceptable" cases, particularly from some of those having only rawinsonde vectors as input, it was decided to establish a more restrictive selection to determine whether improvement could be achieved. The more select class was drawn from among the 88 cases previously selected. The additional criteria are:

- At least 12 vectors,
- rawinsonde data not the major source of vectors, and
- picture quality and registration better than average.

Of the 88 cases, 32 met the additional criteria. Those 32 cases are indicated in table 5 (appendix B) by asterisks.

For this more select group of 32 "good" cases, the requirement for at least 12 vectors was set because the polynomial-fitting techniques appear to yield more realistic solutions on the average when 12 or more input data points are used. Better distribution as well as increased number of data points is a factor. The subjective requirement for above average picture quality is aimed at reducing cloud-vector errors.

## 4. RESULTS AND DISCUSSION

### RMS Errors of Polynomial Solutions

The polynomial-fitting techniques described in appendix A usually permitted a third-degree solution involving 10 variables in x and y. However, a lower degree solution was automatically used if:

(a) The number of input vectors was six or fewer, or
(b) the rms errors for the lower-degree solution were less than 3.0 kt for both the u and v components.

For some groups of results, a lower-degree solution was also retained if:

(c) The results were better than those from the higher-degree solutions (applies to group as a whole), or
(d) the higher-degree solution was rejected because it did not fall within certain specified constraints (applies to individual cases within the group).

Because the rejection scheme is imperfect and the value of the constraints questionable, some of the results for both the "rejection" and "no rejection" situations for the group of 32 good cases are presented.

Table 1 gives average rms differences for the four degrees of equations and for three groupings of cases. This presentation is simply the "goodness of fit" of the input data. In general, third-degree solutions were used to obtain results. However, a few results in this study are based on a plane (zero degree) fit for the entire group of cases.

For group A (all 88 cases) in table 1, the mean rms differences for third-degree solutions are less than 3 kt for both the u and v components. This probably approaches the noise level of the data. Mean rms differences for the 32 good cases (groups B and C) are larger than those for group A because group A includes those cases having less than 12 vectors, whereas groups B and C do not. Generally, the fewer the vectors, the smaller the rms error. Numerical values for group C, third degree, are larger than those for group B because group C, third degree, has incorporated within it nine substituted solutions of second degree.

The highest degree of polynomial actually used for each of the 88 cases is given in table 6, appendix B. Individual rms discrepancies for u and v also are listed.

### Algebraic Sign of Divergence and Vorticity

One would expect the upper level divergence over a tropical cyclone to be strongly positive, and the upper level relative vorticity (except in a small area near the storm center) usually to be negative. The calculations of this study were encouraging in that those expectations, at least, were realized.

Table 1.--Mean rms differences (kt) between the u-v components of the vector input data and the four degrees of best-fit polynomial equations for u and v. For three groupings of cases:

A = all 88 "acceptable" cases (no rejection of polynomial solutions),

B = 32 "good" cases (no rejection of polynomial solutions),

C = 32 good cases (with rejection of third-degree solutions and substitution of second-degree solutions for 9 of the 32 cases).

| | | Degree of polynomial equation* | | | |
|---|---|---|---|---|---|
| | | 0 | 1 | 2 | 3 |
| A | u | 8.66 | 6.14 | 4.81 | 2.51 |
| | v | 8.34 | 5.98 | 4.88 | 2.46 |
| B | u | 8.13 | 6.67 | 5.70 | 3.74 |
| | v | 8.59 | 6.33 | 5.61 | 3.33 |
| C | u | 8.13 | 6.67 | 5.70 | 4.40 |
| | v | 8.59 | 6.33 | 5.61 | 4.12 |

*The degree of polynomial is according to the following scale:

0 = plane fit (3 variables: x, y, constant).
1 = 4 variables (xy, x, y, constant).
2 = second-degree polynomial (6 variables).
3 = third-degree polynomial (10 variables).

Table 2 shows that both the mean divergence (calculated from a plane fit at the center of the grid area) and the divergence above the storm center (calculated from the best-fit polynomial at that point) were nearly always positive for the 88 "acceptable" cases. For the 32 good cases, there were no exceptions. Similar findings obtain for the mean relative vorticity and for the vorticity above the storm center. Both of the latter parameters usually were negative for the 88 cases, and they were always negative for the 32 good cases. One should expect the vorticity above the center to be negative in most cases, as calculated in this study, because that calculation reflects conditions over the middle and outer reaches of the cirrus canopy where most of the input data are located.

For the 32 good cases, it is encouraging that there were no exceptions as to sign, and that some of the more extreme values had been eliminated. Together, these facts support the belief that the group of 32 cases was indeed of better quality than the average of the larger group of 88.

Table 2.--Summary of the numerically calculated estimates of mean divergence, mean vorticity, divergence (above storm center). and vorticity (above storm center) at average elevations at or about 300 mb.

| | Mean div. | Mean vort. | Div. | Vort. |
|---|---|---|---|---|
| For 88 acceptable cases: | | | | |
| Number positive | 85 | 2 | 84 | 15 |
| Number negative | 3 | 86 | 4 | 73 |
| Lowest ($10^{-5}s^{-1}$) | -0.8 | -6.1 | -5.1 | -9.1 |
| Highest ($10^{-5}s^{-1}$) | +4.7 | +0.7 | +7.6 | +7.1 |
| For 32 good cases: | | | | |
| Number positive | 32 | 0 | 32 | 0 |
| Number negative | 0 | 32 | 0 | 32 |
| Lowest ($10^{-5}s^{-1}$) | +0.3 | -6.1 | +0.2 | -9.1 |
| Highest ($10^{-5}s^{-1}$ | +4.4 | -0.5 | +6.1 | -0.3 |

Correlation Coefficients

In addition to the four parameters already mentioned (horizontal divergence, relative vorticity, mean divergence, mean vorticity), a number of others also were calculated. These include the high-level wind, the vertical shear, and various parameter combinations. Correlation coefficients between each of these and the maximum wind speed (MWS) were calculated to discover whether meaningful relationships exist. The same was done with respect to change in storm intensity.

Table 3 gives the coefficients between 5 parameters or combination of parameters and the MWS for the group of 32 cases. The five parameters all include divergence as a positive factor. Three of the five involve the vertical shear as a negatively correlated factor (hence, it appears in the denominator). These relationships are physically realistic. The coefficients, while not large, are significant at the 99% level (the limiting value for 32 pairs is 0.47). Thus, these five parameters appear to be meaningful, both statistically and physically.[4]

---

[4]Of the many parameter combinations tested, a few gave higher values than those shown in table 3, but they could not be justified through physical reasoning.

Scatter diagrams for three of the parameters (mean div., mean div./shear, mean div. x S(0)/shear) vs. MWS are shown in figures 2, 3, and 4, respectively. A complete listing of seven parameters, as numerically calculated for each of the 32 cases, is given in table 7, appendix B.

One might have wished for larger coefficients than those presented in table 3. However, given the known manifold influences that affect tropical storm intensity (e.g., sea-surface temperature, stability, depth of inflow layer, etc.), perhaps it is not reasonable to expect that any one upper level parameter should have a very high correlation with the MWS. This should not eliminate the potential usefulness of the relationships shown here. It is believed that they can be quite helpful, not as final answers but as contributing indicators to be weighed in conjunction with other information.

Table 3.--Correlation coefficients between the maximum wind speed (MWS) and each of five numerically calculated parameters.

| | No rejection of 3d-degree polynomial | With rejection and substitution for 9 of the 32 cases |
|---|---|---|
| Divergence (0)* | 0.485 | 0.485 |
| Mean divergence | 0.486 | 0.486 |
| Divergence/shear | 0.571 | 0.408 |
| Mean div./shear | 0.594 | 0.510 |
| $\frac{\text{Mean div. x S(0)*}}{\text{Shear}}$ | 0.686 | 0.632 |

*(0) denotes calculation from a plane fit for entire group (for that parameter only). S(0) is vertical shear calculated from plane fit.

Some of the scatter in figures 2, 3, and 4 could have been reduced (and some of the coefficients of table 3 improved) by substituting experienced human judgment for the imperfect numerical rejection scheme. As currently programmed, not all unrealistic solutions are rejected by the computer, while some apparently realistic ones are. We hope this scheme can be improved. Meanwhile, we show the undoctored machine results as indicators of the present capability of the system in the purely mechanical sense.

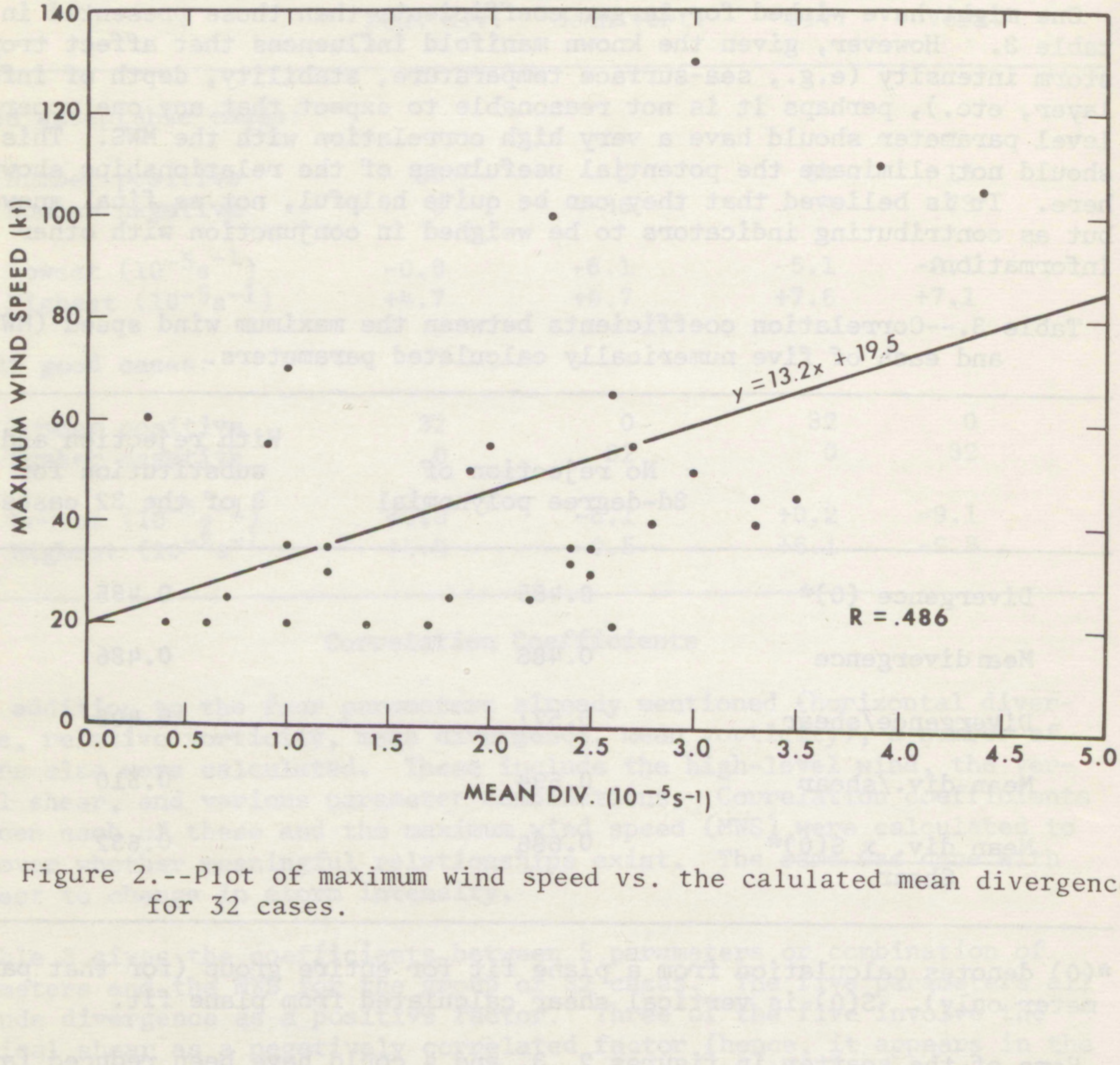


Figure 2.--Plot of maximum wind speed vs. the calulated mean divergence for 32 cases.

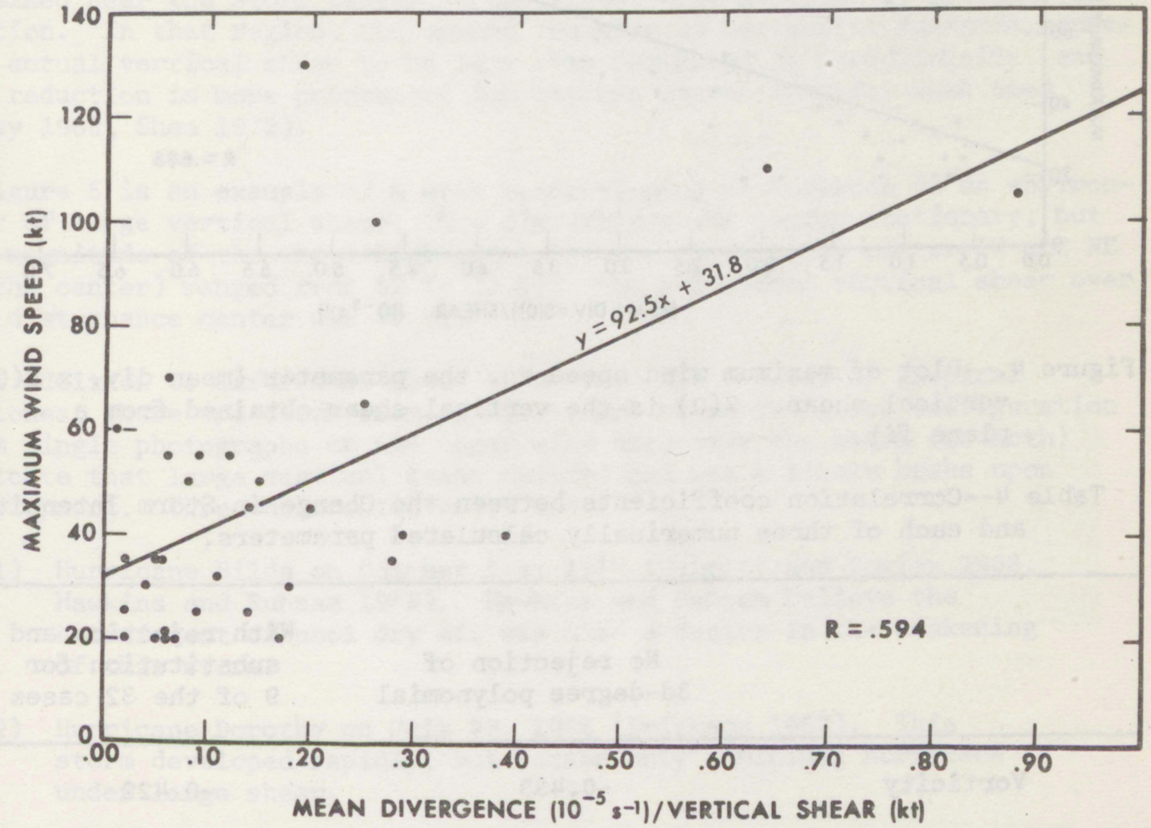


Figure 3.--Plot of maximum wind speed vs. the parameter mean divergence/vertical shear.

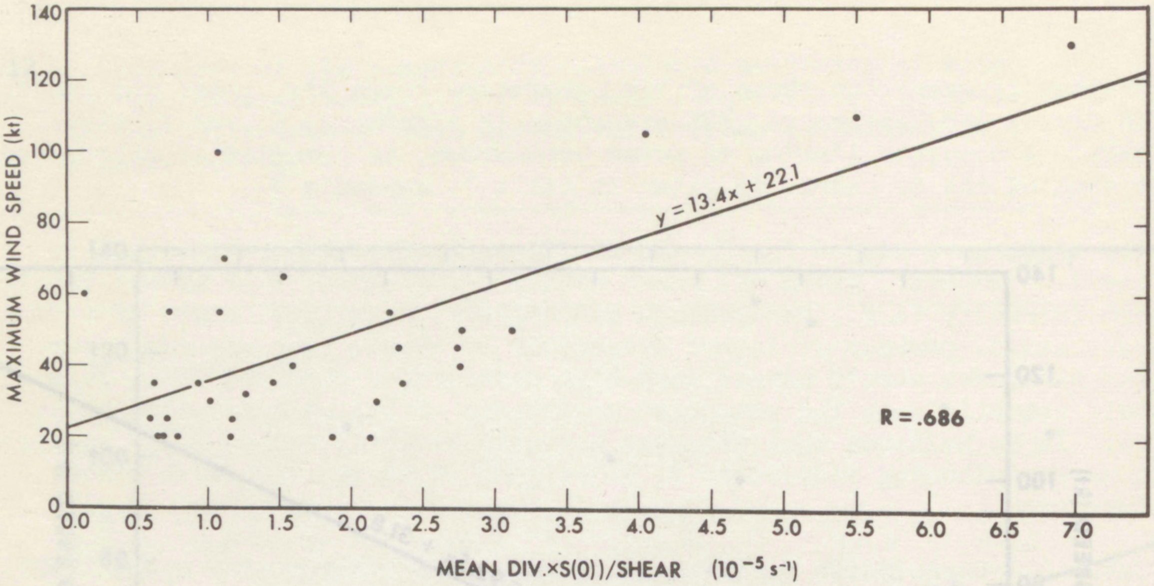


Figure 4.--Plot of maximum wind speed vs. the parameter (mean div. x S(0))/ vertical shear. S(0) is the vertical shear obtained from a plane fit.

Table 4--Correlation coefficients between the Change in Storm Intensity and each of three numerically calculated parameters.

| | No rejection of 3d-degree polynomial | With rejection and substitution for 9 of the 32 cases |
|---|---|---|
| Vorticity | -0.433 | -0.422 |
| Vorticity (2)* | -0.554 | -0.554 |
| Mean div. - vorticity | .496 | .466 |

*(2) denotes calculation from 2d-degree polynomials for entire group.

Table 4 gives correlation coefficients between change in storm intensity and three calculated parameters. These relationships generally are inferior to those for storm intensity itself (shown in table 3). The better coefficients in table 4 are only marginally significant. One reason for this showing may be the rather crude four-category stratification for change in intensity, as defined in table 5, appendix B. Nevertheless, it is interesting that relative vorticity is the parameter that tends to be related to change in intensity, whereas the intensity itself is much better related to divergence.

## Some Qualitative Findings

A negative correlation between vertical shear and storm intensity has already been shown. The author feels that the real relationship probably is better than the ATS 3 data indicated because few high-level vectors are obtained near the storm center -- the region most affected by intense convection. In that region, the upward transfer of horizontal momentum causes the actual vertical shear to be less than indicated by baroclinicity, and the reduction is more pronounced for intense storms than for weak ones (Gray 1968, Shea 1972).

Figure 5 is an example of a weak nondeveloping disturbance in an environment of large vertical shear. The disturbance was nearly stationary, but the magnitude of the three high-cloud vectors nearest the center (N and NE of the center) ranged from 52 to 72 kt. The calculated vertical shear over the disturbance center was 46 kt.

In addition to inferences about shear from ATS 3 views of tropical cyclones, there are cases from earlier years where the cloud configuration from single photographs or the upper wind data over the storm (or both) indicate that large vertical shear existed and was a likely brake upon development. Three documented cases are:

(1) Hurricane Hilda on October 2-4, 1964 (Merritt and Bowley 1968; Hawkins and Rubsam 1968). Hawkins and Rubsam believe the entrainment of cool dry air was also a factor in the weakening of this storm.

(2) Hurricane Dorothy on July 23, 1966 (Erickson 1967). This storm developed rapidly, but became only a minimal hurricane under large shear.

(3) Hurricane Inez on October 3, 1966 (Merritt and Bowley 1968). Inez was a weak storm on this date. It was more intense both earlier and later.

The foregoing, plus observations of the present study, suggest the following qualitative rules with respect to vertical shear over the storm center:

- Large vertical shear over weak ($\lesssim$ 35 kt) disturbances inhibits development (Alma, May 22-24, 1970; unnamed, June 17-20, 1972).

- Tropical storms and hurricanes with large cloud extensions toward the east or northeast, and with evidence of strong west or southwest winds over the cloud extension, usually are not intensifying or are intensifying only slowly. If such a storm is a hurricane, it tends to be of minimal hurricane intensity (Abby, June 3-5, 1968; Brenda, June 21, 1968; Agnes, June 16-19, 1972).

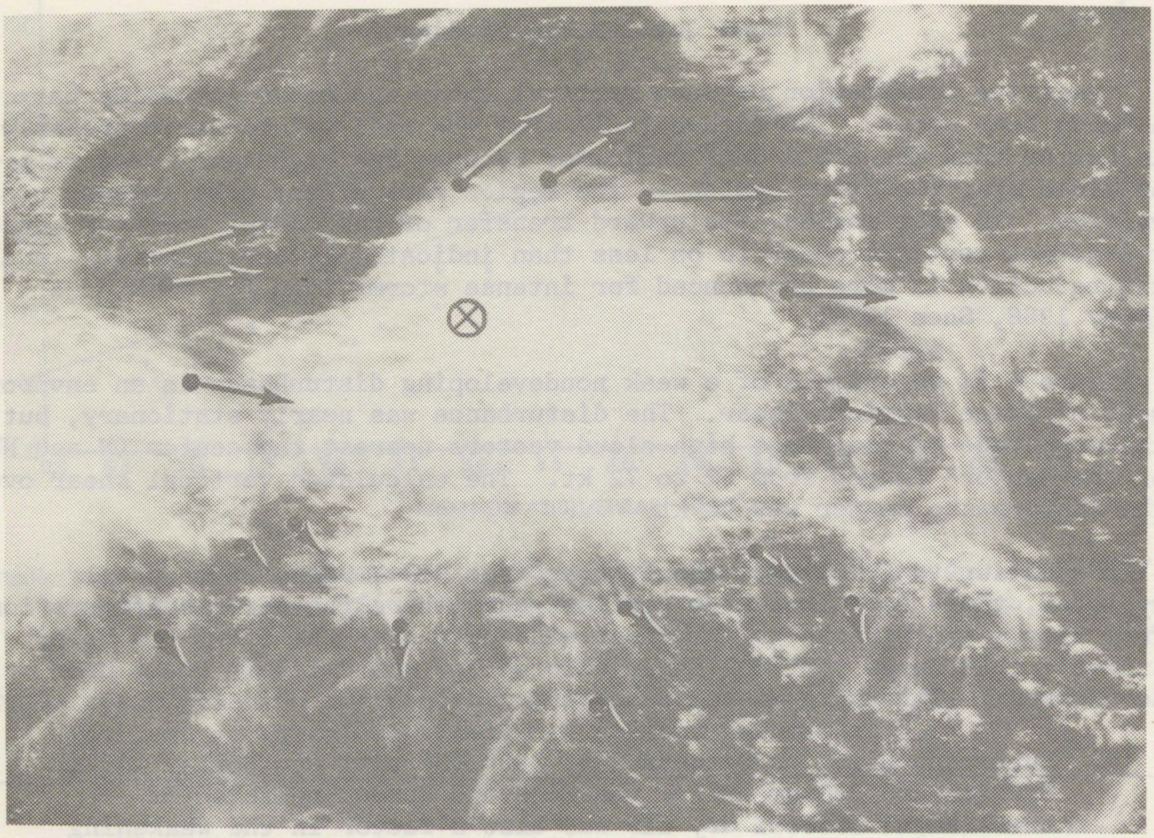

Figure 5.--A weak nondeveloping disturbance with large vertical wind shear over central area, June 17, 1972.

- Storms embedded in a deep layer of small vertical shear ($\leq$ 20 kt) may intensify rapidly (Celia, Aug. 3, 1970; Edith, Sept. 8-9, 1971).

- Recurved storms embedded in the westerlies may also intensify if the storm is moving rapidly in the same general direction as the upper cloud vectors (Blanche, Aug. 11, 1969; Beth, Aug. 14, 1971).

The above rules involve inferences about the vertical shear at or very near the storm center. In contrast, there is the situation in which large vertical shear may be observed at some distance from the center. A suggested rule under the latter category is:

- Large north-south vertical shear in the southeast quadrant of the storm, several degrees of latitude removed from the center, is favorable for storm intensification.

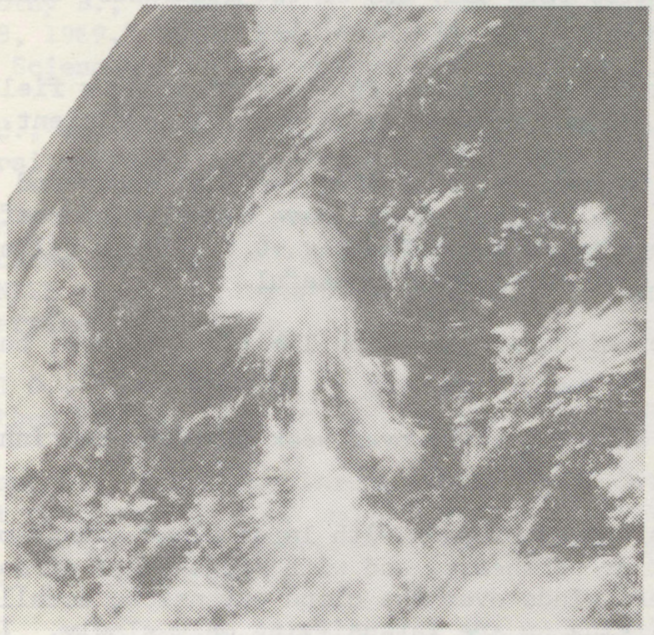

Figure 6.--A severe and still-intensifying hurricane with very large north-south vertical shear over the SE quadrant feeder band -- Hurricane Camille, Aug. 16, 1969

In the present study, the outstanding example of this is hurricane Camille on Aug. 16, 1969 (fig. 6). Very large shear was evident in the differential cloud motions of the southeast quadrant feeder band. Measured values from rawinsonde data over Kingston, Jamaica, were as large as 75 kt. Such large shear indicates both the intense warm core to the west and northwest and the relatively cold air to the east. The importance of the environmental cold source for storm development has been pointed out by Riehl (1954).

## 5. CONCLUSIONS

- High-cloud vectors over tropical cyclones can give statistically useful indications of storm intensity, <u>provided</u> the following conditions exist:

  (1) Good registration and picture quality,
  (2) careful measurement of vectors, and
  (3) good distribution (at least 12 vectors over three or four quadrants of the storm).

Item (3) is particularly important. A four-quadrant distribution is desirable. Vectors from only one or two quadrants, unless of unusually large magnitude, are of little help.

- Rawinsonde data may be very helpful in augmenting a field of cloud vectors. Alone, rawinsonde data are insufficient.

- The calculated parameters, mean div, vertical shear and (mean div. x S(0))/vertical shear, have correlation coefficients with storm intensity of approximately +0.6. It is believed these parameters could be operationally useful.

The following conclusions are based on limited evidence, but are believed valid:

- Large vertical shear directly over weak disturbances inhibits development.

- Tropical storms and hurricanes with large cloud extensions toward the east or northeast, and with evidence of strong west or southwest winds over the cloud extension, usually are not intensifying or are intensifying only slowly. If such a storm is a hurricane, it tends to be of minimal hurricane intensity.

- Storms embedded in a deep layer of small vertical shear may intensify rapidly.

- Recurved storms embedded in the westerlies may also intensify if the storm is moving rapidly in the same general direction as the upper cloud vectors.

- Large north-south vertical shear in the southeast quadrant of a storm, several degrees removed from the center, is a sign of storm intensification.

## ACKNOWLEDGMENTS

Some of the ATS 3 film loops were obtained from Prof. T. T. Fujita, University of Chicago. (These were among the best quality pictures available.) Mr. Michael T. Young, Analysis Branch, NESS, assisted in obtaining many of the vector sets through use of their operational program. A number of sub-programs used in the polynomial-fitting technique, as well as programming advice, were furnished by Dr. C. M. Hayden. The assistance of all of these persons is gratefully acknowledged.

REFERENCES

Bradbury, Dorothy L., "The Filling over Land of Hurricane Camille, August 17-18, 1969," SMRP Research Paper No. 96, Dept. of the Geophysical Sciences, The University of Chicago, Aug. 1971, 25 pp.

Dunn, Gordon E., and Miller, Banner I., Atlantic Hurricanes, Louisiana State University Press, 1964, chapters 7-11, pp. 129-205.

Dvorak, Vernon F., "A Technique for the Analysis and Forecasting of Tropical Cyclone Intensities from Satellite Pictures," NOAA Technical Memorandum NESS 45, U. S. Department of Commerce, National Environmental Satellite Service, Washington, D. C., Feb. 1973, 19 pp.

Erickson, Carl O., "Some Aspects of the Development of Hurricane Dorothy," Monthly Weather Review, Vol. 95, No. 3, Mar. 1967, pp. 121-130.

Estoque, Mariano A., "Hurricane Intensity and Upper Level Cloudiness," Final Report prepared for NOAA under Grant No. 0-35178, Division of Atmospheric Science, The University of Miami, Coral Gables, Fla., Oct. 1971, 11 pp. plus figures.

Fett, Robert W., "Some Characteristics of the Formative Stage of Typhoon Development: A Satellite Study," Unpublished paper presented at National Conference on Physics and Dynamics of Clouds, Chicago, Ill., March 24-26, 1964.

Fritz, Sigmund, Hubert, Lester F., and Timchalk, Andrew, "Some Inferences from Satellite Pictures of Tropical Disturbances," Monthly Weather Review, Vol. 94, No. 4, Apr. 1966, pp. 231-236.

Fujita, T. T., and Black, Peter G., "In-and Outflow Field of Hurricane Debbie as Revealed by Echo and Cloud Velocities from Airborne Radar and ATS-III Pictures," SMRP Research Paper No. 93, Department of the Geophysical Sciences, The University of Chicago, Nov. 1970, 6 pp.

Gray, William M., "Global View of the Origin of Tropical Disturbances and Storms," Monthly Weather Review, Vol. 96, No. 10, Oct. 1968, pp. 669-700.

Gray, William M., "A Climatology of Tropical Cyclones and Disturbances of the Western Pacific with a Suggested Theory for their Genesis/ Maintenance," NAVWEARSCHFAC Technical Paper No. 19-70, U. S. Navy Weather Research Facility, Norfolk, Va., Nov. 1970, 224 pp.

Gruber, Arnold, Herman, Leroy, and Krueger, A. F., "The Use of Satellite Cloud Motions for Estimating the Circulation over the Tropics," Monthly Weather Review, Vol. 99, No. 10, Oct. 1971, pp. 739-743.

Hawkins, Harry F., and Rubsam, Daryl T., "Hurricane Hilda, 1964: III. Degradation of the Hurricane," Monthly Weather Review, Vol. 96, No. 10, Oct. 1968, pp. 701-707.

Hubert, Lester F., and Timchalk, Andrew, "Estimating Hurricane Wind Speeds from Satellite Pictures," Monthly Weather Review, Vol. 97, No. 5, May 1969, pp. 382-383.

Hubert, L. F., and Whitney, L. F., Jr., "Wind Estimation from Geostationary-Satellite Pictures," Monthly Weather Review, Vol. 99, No. 9, Sept. 1971, pp. 665-672.

Merritt, Earl S., "Atlantic Upper Tropospheric Circulations and Tropical Cyclone Development," Final Report under Contract No. N 189-(188)-60598A, U. S. Navy Weather Research Facility, Norfolk, Va., May 1967, 91 pp.

Merritt, Earl S., and Bowley, Clinton J., "Cirrus Canopy Evolution in Selected Atlantic Hurricanes," Final Report prepared for National Environmental Satellite Center under Contract No. E-206-67(N), Allied Research Associates, Inc., Concord, Mass., May 1968, 93 pp.

Panofsky, Hans A., and Brier, Glenn W., Some Applications of Statistics to Meteorology, The Pennsylvania State University, University Park, Pa., 1958, 224 pp.

Riehl, Herbert, Tropical Meteorology, McGraw-Hill Book Company, Inc., New York, N. Y., 1954, chapter 11, pp. 281-357.

Schmidt, Phillip J., and Johnson, Donald R., "Use of Approximating Polynomials to Estimate Profiles of Wind, Divergence, and Vertical Motion," Monthly Weather Review, Vol. 100, No. 5, May 1972, pp. 345-353.

Shea, Dennis J., "The Structure and Dynamics of the Hurricane's Inner Core Region," Atmospheric Science Paper No. 182, Project Leader: William M. Gray, Colorado State University, Fort Collins, Colo., Apr. 1972, 134 pp.

Simpson, R. H., and Hebert, Paul J., "Atlantic Hurricane Season of 1972," Monthly Weather Review, Vol 101, No. 4, Apr. 1973, pp. 323-333.

Simpson, R. H., and Hope, John R., "Atlantic Hurricane Season of 1971," Monthly Weather Review, Vol. 100, No. 4, Apr. 1972, pp. 256-267.

Simpson, R. H., and Pelissier, Joseph M., "Atlantic Hurricane Season of 1970," Monthly Weather Review, Vol. 99, No. 4, Apr. 1971, pp. 269-277.

Simpson, R. H., Sugg, Arnold L., and Staff, "The Atlantic Hurricane Season of 1969," Monthly Weather Review, Vol. 98, No. 4, Apr. 1970, pp. 293-306.

Smith, Clark L., "On the Intensification of Hurricane Celia (1970)," NOAA Technical Memorandum, ERL NHRL-100, National Hurricane Research Laboratory, Coral Gables, Fla., Aug. 1972, 35 pp.

Sugg, Arnold L., and Hebert, Paul J., "The Atlantic Hurricane Season of 1968," Monthly Weather Review, Vol. 97, No. 3, Mar. 1969, pp. 225-239.

Timchalk, A., Unpublished analyses of cloud vector fields in tropical cyclones, prepared in the Meteorological Satellite Laboratory, NESS, NOAA, U. S. Department of Commerce, Washington, D. C.

Young, Michael T., Doolittle, Russell C., and Mace, Lee M., "Operational Procedures for Estimating Wind Vectors from Geostationary Satellite Data," NOAA Technical Memorandum NESS 39, U. S. Department of Commerce, National Environmental Satellite Service, Washington, D. C., July 1972, 19 pp.

## APPENDIX A: DESCRIPTION OF POLYNOMIAL-FITTING TECHNIQUE

The technique is a modified version of that reported by Schmidt and Johnson (1972), as applied to the horizontal wind field. Input wind data (location, speed, direction) for up to 25 vector locations are separated into u and v components. The program calculates best-fit polynomial equations separately for each component, using least-squares regression methods. Explained variance, rms errors, and the solution deviations from individual input vectors are obtained as by-products. The numerical solutions for u and v are then used to specify the horizontal fields of wind, divergence, vorticity, and other parameters.

It is stressed that this technique will yield useful results only within the data network. Extrapolation to exterior regions is not warranted. Even over the interior, solutions from second- and third-degree polynomials occasionally are unrealistic if the input data are sparse or their distribution is poor.

Figure 7* shows the wind field from an acceptable third-degree polynomial solution. Solution vectors over the interior agree fairly well with the input data (rms errors for u and v are 4.8 and 3.2 kt, respectively). The dotted line marks the perimeter of the input data, beyond which the solution becomes unrealistic. Corresponding fields of divergence and vorticity are presented in figure 8.

Modifications from Schmidt and Johnson (1972) include the following:

(1) For each case, for u and v, four degrees of polynomial were computed:

(a) Plane fit (3 variables: x, y, constant),
(b) four variables (xy, x, y, constant),
(c) second-degree polynomial (6 variables), and
(d) third-degree polynomial (10 variables).

(2) For each case, and for each degree of polynomial computation (except plane fit) for u and v, the coordinate axes were rotated with respect to the input data through an arc of 90° at 5-degree increments. Of the 18 choices, the solution having the smallest rms error was selected.

(3) For each case, the higher degrees of polynomial (beyond the plane fit) were tested against certain criteria so that possible unrealistic solutions might be rejected. At the center of the grid, the solution under consideration was compared with the next lower-degree accepted solution at the same point. The criteria are:

*The designator "NTV" in the computerized legends of this and subsequent figures indicates the number of variables in the polynomial. Thus, "NTV = 10" indicates a third-degree polynomial (10 variables).

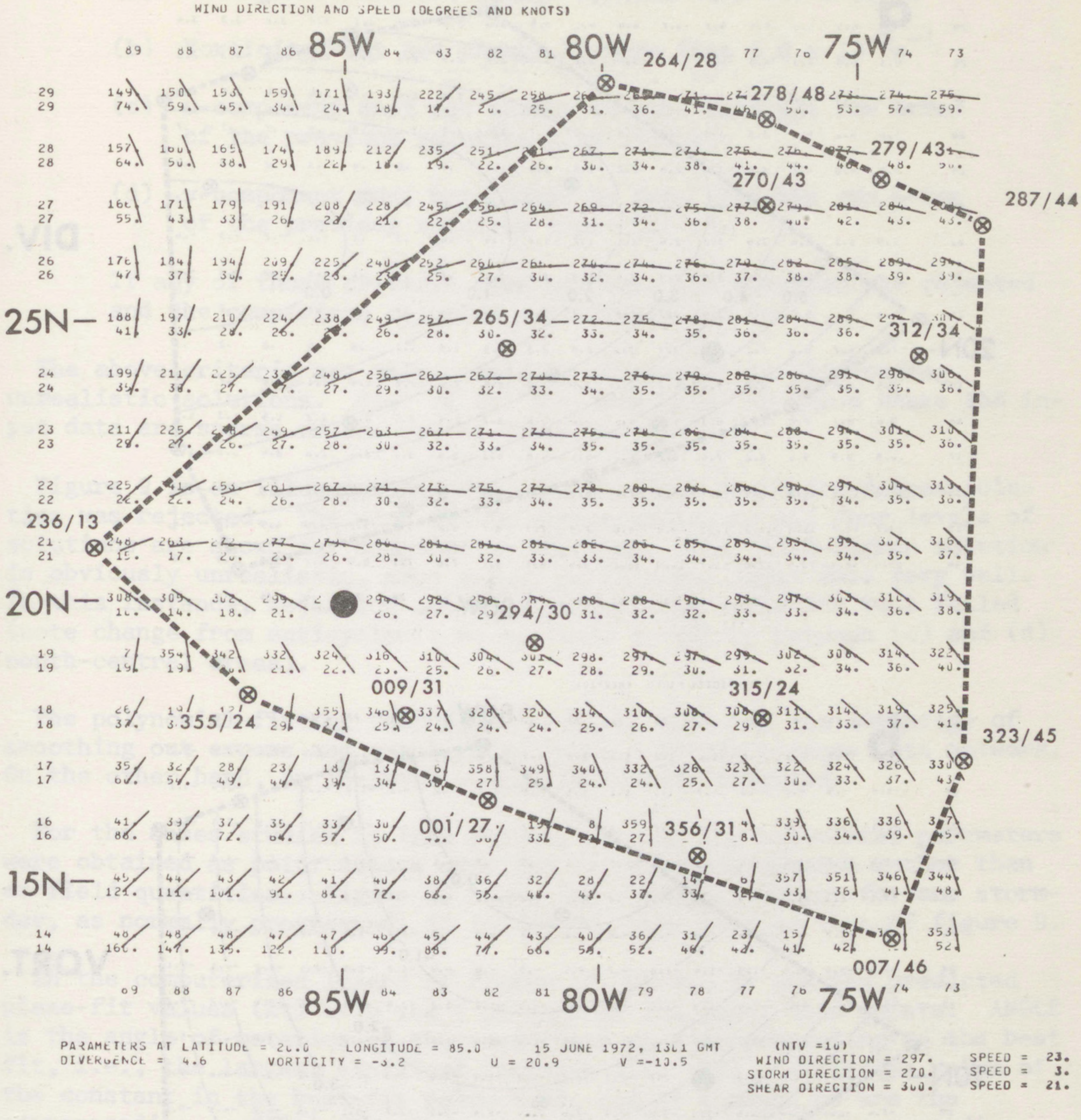


Figure 7.--Wind field from an acceptable third-degree polynomial solution. Locations of disturbance center and the vector input data also are shown. (Wind field outside the data perimeter is unrealistic. pre-Agnes, June 15, 1972).

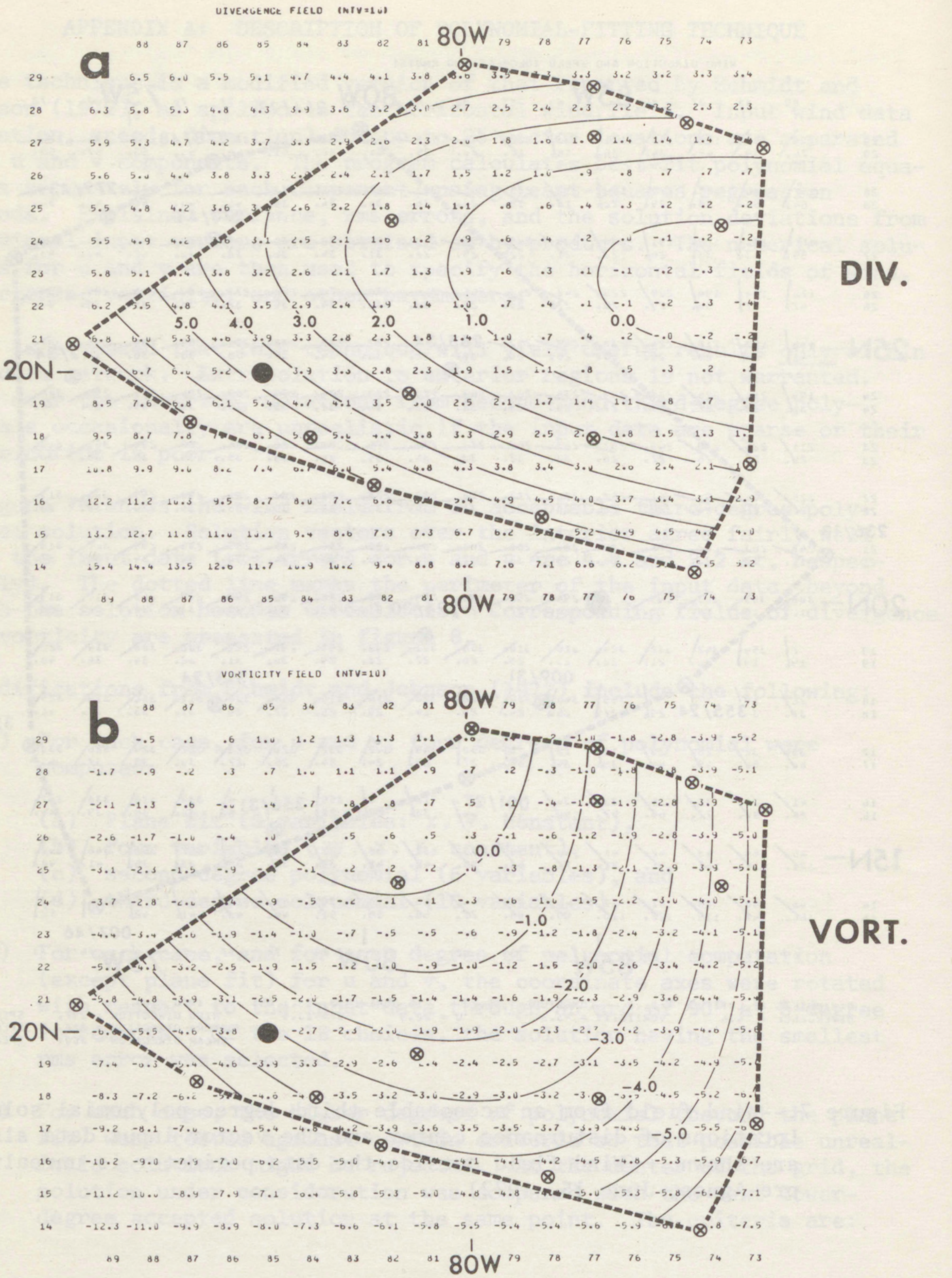


Figure 8--(a) Divergence and (b) vorticity fields corresponding to wind field shown in figure 7. (calculations outside data perimeter are unrealistic.)

(a) Divergence must not change by more than $3.0 \times 10^{-5}s^{-1}$

(b) Vorticity must not change by more than $3.0 \times 10^{-5}s^{-1}$

(c) u-component must not change by more than the rms error of the previous solution plus 10.0 kt.

(d) v-component must not change by more than the rms error of the previous solution plus 10.0 kt.

If any of those criteria were not met, the solution was rejected and the comparison solution substituted for it.

The above criteria are only partially successful in eliminating unrealistic solutions. Most of the problems arise in cases where the input data are sparse or are poorly distributed.

Figure 9 is an illustration of a case in which the third-degree solution was rejected. The wind fields corresponding to all four levels of solutions are shown for comparative purposes. The third-degree solution is obviously unrealistic, even though it fits the input data very well. In this instance, rejection occurred because the vorticity test failed (note change from anticyclonic to cyclonic vorticity between (c) and (d) north-central areas).

The polynomial-fitting technique described here has the advantage of smoothing out errors and meaningless "noise" within a dense data network. On the other hand, an isolated vector is heavily weighted.

For the cases studied in this report, most of the calculated parameters were obtained as point values over the storm or disturbance rather than as field quantities. Figure 10 shows the numerical output for one storm-day, as normally programmed; it is for the same case as that of figure 9.

In the computerized legend of figure 10, UP and VP are the predicted plane-fit values (kt) of u and v at each of the input data points. ANGLE is the angle of rotation of the coordinate axes corresponding to the best fit, i.e., the largest explained variance (EX. VAR). A0 is the value of the constant in the best-fit polynomial, and A1 through A9 are the corresponding coefficients of x and y and powers thereof, in ascending order.

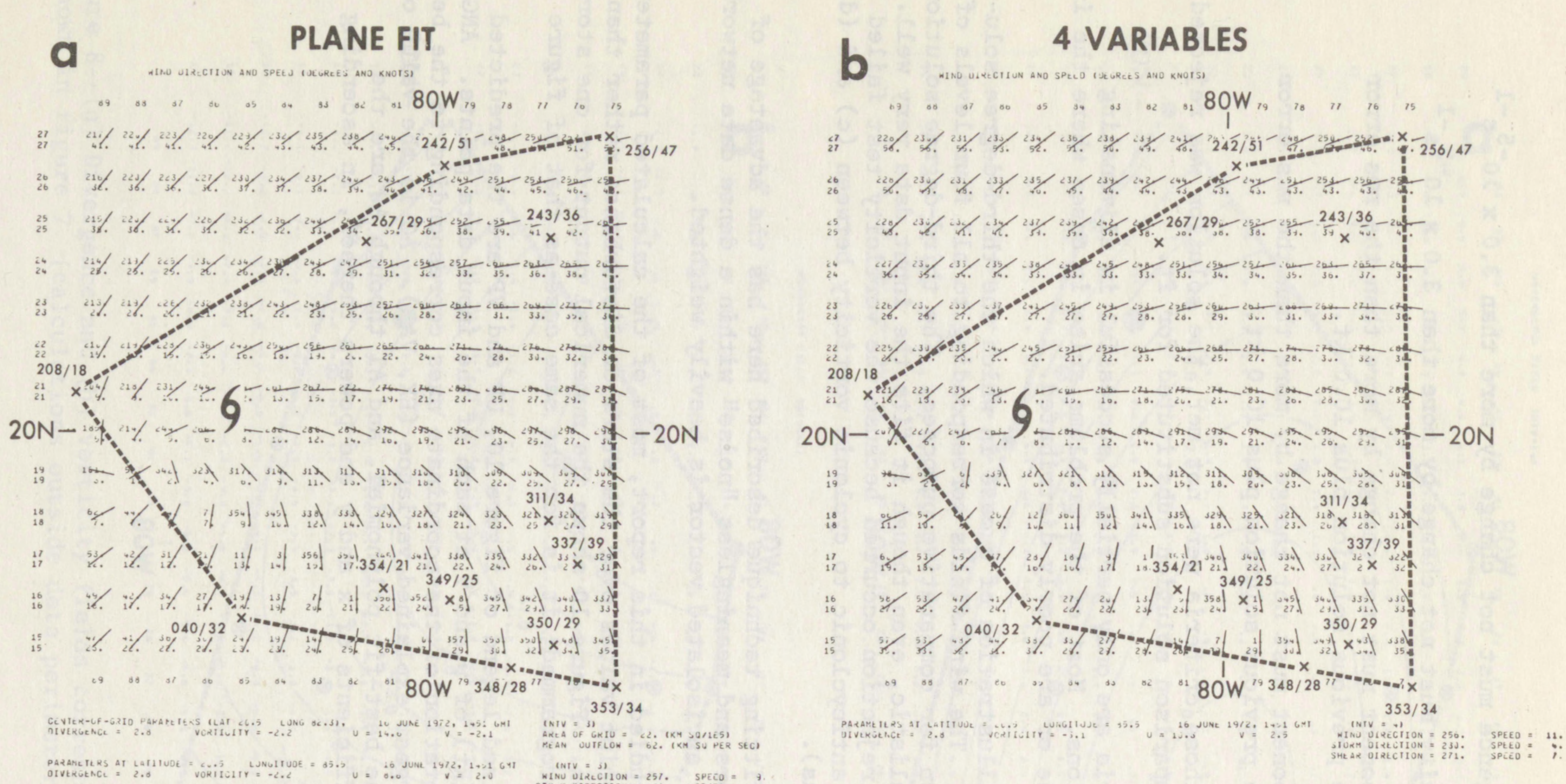


Figure 9.--Wind fields for two different degrees of polynomial fit, including a rejected third-degree solution: (a) plane fit, (b) four variables. Locations of storm center and the vector input data are also shown. (Tropical storm Agnes, June 16, 1972).

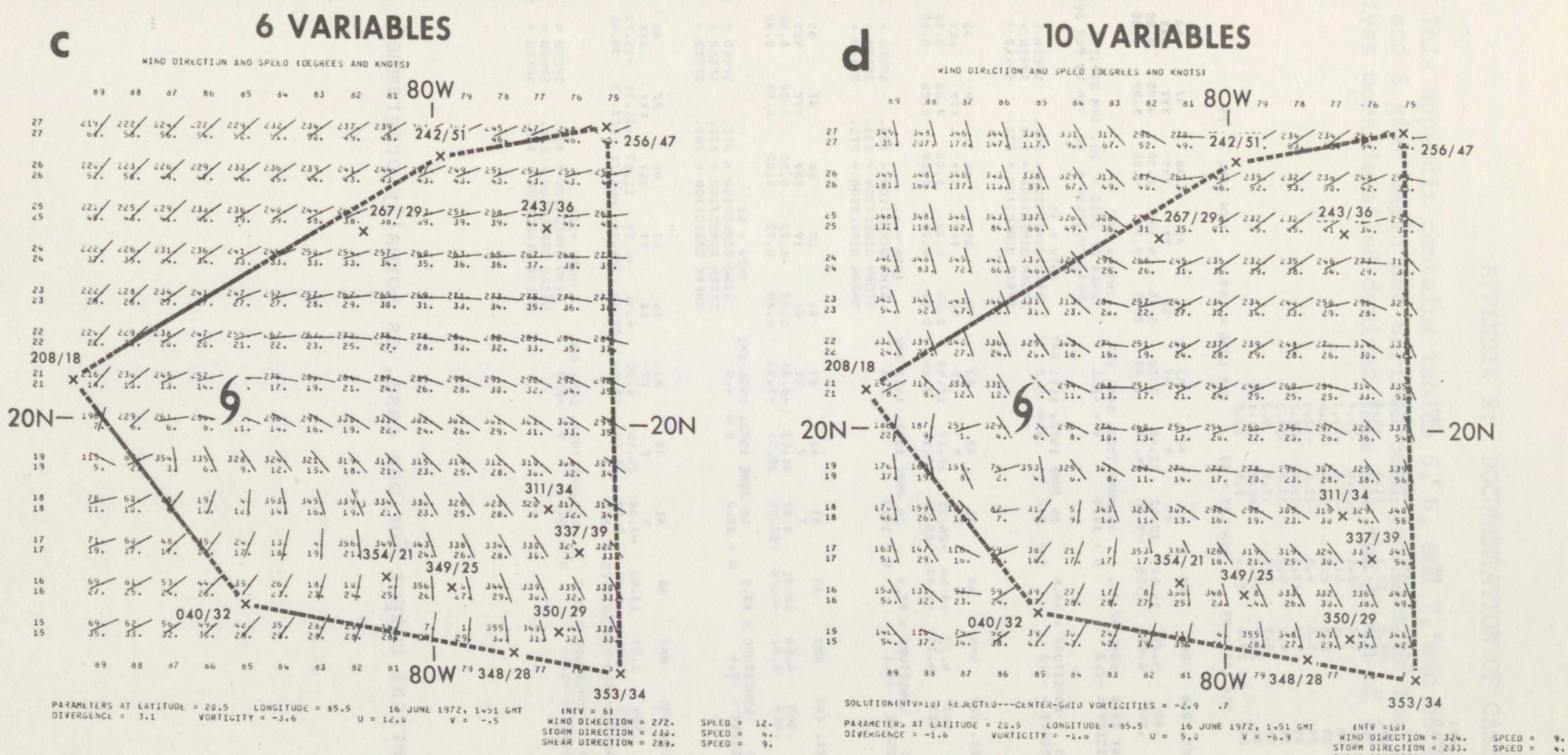


Figure 9.--Continued. (c) second-degree polynomial (6 variables), (d) the rejected third-degree polynomial (10 variables).

INPUT DATA (16 JUNE 1972, 1451 GMT)

| LAT | LONG | DIR | SPEED | U | UP | V | VP |
|---|---|---|---|---|---|---|---|
| 26.4 | 79.7 | 242 | 51 | 45.0 | 39.4 | 23.9 | 18.0 |
| 24.7 | 76.8 | 243 | 36 | 32.1 | 38.9 | 16.3 | 7.3 |
| 27.1 | 75.2 | 256 | 47 | 45.6 | 50.1 | 11.4 | 14.8 |
| 15.6 | 85.1 | 40 | 32 | -20.6 | -7.5 | -24.5 | -18.3 |
| 16.3 | 81.2 | 354 | 21 | 2.2 | 2.1 | -20.9 | -20.7 |
| 16.0 | 79.4 | 349 | 25 | 4.8 | 4.4 | -24.5 | -24.3 |
| 14.5 | 77.8 | 348 | 28 | 5.8 | 2.2 | -27.4 | -32.4 |
| 14.9 | 76.6 | 350 | 29 | 5.0 | 5.8 | -28.6 | -32.4 |
| 16.9 | 76.0 | 337 | 39 | 15.2 | 13.7 | -35.9 | -25.2 |
| 14.0 | 74.9 | 353 | 34 | 4.1 | 5.8 | -33.7 | -38.3 |
| 20.9 | 89.7 | 208 | 18 | 8.5 | 2.2 | 15.9 | 9.2 |
| 17.9 | 76.8 | 311 | 34 | 25.7 | 15.7 | -22.3 | -20.1 |
| 24.6 | 81.8 | 267 | 29 | 29.0 | 29.4 | 1.5 | 13.5 |

13 STATIONS USED MAX LAT = 27 MIN LAT = 15 MAX LONG = 89 MIN LONG = 75

| | ANGLE | EX. VAR | RMS | A0 | A1<br>X | A2<br>Y | A3<br>XY | A4<br>XX | A5<br>YY | A6<br>XXY | A7<br>XYY | A8<br>XXX | A9<br>YYY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U COMPONENT (NTV= 3) | 0. | .901 | 5.74 | 14.63 | 13.62 | 22.40 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| V COMPONENT (NTV= 3) | 0. | .905 | 6.44 | -2.09 | -9.86 | 26.35 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

CENTER-OF-GRID PARAMETERS (LAT 20.5 LONG 82.3), 16 JUNE 1972, 1451 GMT (NTV = 3)
DIVERGENCE = 2.8 VORTICITY = -2.2 U = 14.6 V = -2.1
AREA OF GRID = 22. (KM SQ/1E5)
MEAN OUTFLOW = 62. (KM SQ PER SEC)

PARAMETERS AT LATITUDE = 20.5 LONGITUDE = 85.5 16 JUNE 1972, 1451 GMT (NTV = 3)
DIVERGENCE = 2.8 VORTICITY = -2.2 U = 8.6 V = 2.0
WIND DIRECTION = 257. SPEED = 9.
STORM DIRECTION = 230. SPEED = 4.
SHEAR DIRECTION = 276. SPEED = 6.

| | ANGLE | EX. VAR | RMS | A0 | A1<br>X | A2<br>Y | A3<br>XY | A4<br>XX | A5<br>YY | A6<br>XXY | A7<br>XYY | A8<br>XXX | A9<br>YYY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U COMPONENT (NTV= 4) | 80. | .943 | 4.37 | 15.46 | -26.51 | 17.17 | 12.48 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| V COMPONENT (NTV= 4) | 80. | .907 | 6.35 | -1.85 | -29.65 | -5.17 | 3.64 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

PARAMETERS AT LATITUDE = 20.5 LONGITUDE = 85.5 16 JUNE 1972, 1451 GMT (NTV = 4)
DIVERGENCE = 2.8 VORTICITY = -3.1 U = 10.3 V = 2.5
WIND DIRECTION = 256. SPEED = 11.
STORM DIRECTION = 230. SPEED = 4.
SHEAR DIRECTION = 271. SPEED = 7.

| | ANGLE | EX. VAR | RMS | A0 | A1<br>X | A2<br>Y | A3<br>XY | A4<br>XX | A5<br>YY | A6<br>XXY | A7<br>XYY | A8<br>XXX | A9<br>YYY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U COMPONENT (NTV= 6) | 10. | .948 | 4.16 | 18.31 | 8.67 | 31.03 | -8.81 | 1.53 | -8.23 | 0.00 | 0.00 | 0.00 | 0.00 |
| V COMPONENT (NTV= 6) | 0. | .919 | 5.92 | -6.78 | -13.02 | 28.31 | -3.53 | 4.89 | 6.72 | 0.00 | 0.00 | 0.00 | 0.00 |

PARAMETERS AT LATITUDE = 20.5 LONGITUDE = 85.5 16 JUNE 1972, 1451 GMT (NTV = 6)
DIVERGENCE = 3.1 VORTICITY = -3.6 U = 12.0 V = -.5
WIND DIRECTION = 272. SPEED = 12.
STORM DIRECTION = 230. SPEED = 4.
SHEAR DIRECTION = 289. SPEED = 9.

| | ANGLE | EX. VAR | RMS | A0 | A1<br>X | A2<br>Y | A3<br>XY | A4<br>XX | A5<br>YY | A6<br>XXY | A7<br>XYY | A8<br>XXX | A9<br>YYY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U COMPONENT (NTV=10) | 60. | .984 | 2.27 | 13.63 | -3.88 | 28.16 | 8.50 | 4.91 | -6.29 | 11.67 | -31.51 | -11.72 | -7.27 |
| V COMPONENT (NTV=10) | 50. | .998 | .92 | 3.06 | 7.08 | 32.06 | 12.06 | -75.39 | 15.34 | -46.71 | -122.63 | 39.65 | -35.56 |

SOLUTION(NTV=10) REJECTED---CENTER-GRID VORTICITIES = -2.9 .7

PARAMETERS AT LATITUDE = 20.5 LONGITUDE = 85.5 16 JUNE 1972, 1451 GMT (NTV =10)
DIVERGENCE = -1.6 VORTICITY = -1.6 U = 5.0 V = -6.9
WIND DIRECTION = 324. SPEED = 9.
STORM DIRECTION = 230. SPEED = 4.
SHEAR DIRECTION = 348. SPEED = 10.

Figure 10.--Numerical output for one case, as normally programmed.

## APPENDIX B: DOCUMENTATION OF CASES

This appendix contains tables 5, 6, and 7, and notes thereto. Tables 5 and 6 give basic and derived data for each of the 88 cases. Table 7 gives more detailed derived data for the group of 32 good cases.

Table 5.--List of 88 acceptable cases (identification, disturbance location and intensity, and source and number of high-level vectors).

| Case* no. | Date | Time (GMT) bgng. | end | Storm name | Location lat. (°N) | long. (°W) | MWS (kt) | Change | Vectors source | no. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. | 01 June 1968 | 1200 | ---- | (pre-Abby) | 17.5 | 85.8 | 20 | 0 | 5 | 7 |
| 2. | 02 " " | 0000 | ---- | " " | 18.9 | 85.9 | 25 | + | 5 | 7 |
| 3. | 03 " " | 0000 | ---- | ABBY | 22.0 | 84.0 | 45 | + | 5 | 7 |
| 4. | 03 " " | 1200 | ---- | " | 24.5 | 83.5 | 55 | 0 | 5 | 7 |
| 5. | 04 " " | 0000 | ---- | " | 25.5 | 83.2 | 60 | 0 | 5 | 8 |
| 6. | 05 " " | 1319 | 1449 | " | 28.0 | 80.3 | 55 | 0 | 4,5 | 8 |
| 7. * | 21 June 1968 | 1123 | 1309 | BRENDA | 30.0 | 75.5 | 45 | + | 2 | 25 |
| 8. * | 21 " " | 1618 | 1819 | " | 30.0 | 74.7 | 50 | + | 2 | 25 |
| 9. * | 21 " " | 1832 | 2046 | " | 30.0 | 74.4 | 55 | + | 2 | 25 |
| 10. * | 21 June 1968 | 1820 | 2047 | (pre-Candy) | 19.5 | 95.5 | 20 | + | 3,5 | 14 |
| 11. * | 22 " " | 1536 | 1725 | " " | 20.5 | 96.0 | 30 | + | 2 | 21 |
| 12. * | 22 " " | 1725 | 1911 | " " | 21.0 | 96.0 | 32 | + | 2 | 25 |
| 13. * | 22 " " | 1938 | 2124 | " " | 21.5 | 96.0 | 35 | + | 2 | 25 |
| 14. * | 23 " " | 1827 | 2030 | CANDY | 26.8 | 96.8 | 45 | + | 2 | 25 |
| 15. * | 23 " " | 2030 | 2203 | " | 27.3 | 97.0 | 50 | + | 2 | 25 |
| 16. | 12 Aug. 1968 | 1309 | 1604 | DOLLY | 35.4 | 70.3 | 45 | + | 3,5 | 13 |
| 17. | 13 Aug. 1969 | 1200 | ---- | pre-Camille | 17.5 | 76.2 | 25 | 0 | 5 | 10 |
| 18. | 14 " " | 0000 | ---- | " " | 18.0 | 78.5 | 30 | + | 5 | 12 |
| 19. | 14 " " | 1200 | ---- | CAMILLE | 18.8 | 81.0 | 40 | ++ | 5 | 7 |
| 20. | 15 " " | 0000 | ---- | " | 19.7 | 82.7 | 55 | ++ | 5 | 12 |
| 21. | 15 " " | 1200 | ---- | " | 20.6 | 83.8 | 80 | ++ | 5 | 8 |
| 22. | 16 " " | 0000 | ---- | " | 22.5 | 84.6 | 110 | ++ | 5 | 14 |
| 23. | 16 " " | 1200 | ---- | " | 23.8 | 85.7 | 130 | ++ | 5 | 13 |
| 24. | 17 " " | 0000 | ---- | " | 25.2 | 87.2 | 150 | ++ | 5 | 12 |
| 25. | 17 " " | 1200 | ---- | " | 27.0 | 88.0 | 170 | + | 5 | 12 |
| 26. | 18 Aug. 1969 | 1213 | 1353 | DEBBIE | 20.0 | 54.0 | 98 | 0 | 4 | 12 |
| 27. | 18 " " | 1718 | 2020 | " | 20.5 | 54.5 | 88 | - | 4 | 15 |
| 28. | 19 " " | 1202 | 1407 | " | 23.0 | 58.5 | 80 | + | 4 | 12 |
| 29. | 19 " " | 1807 | 2012 | " | 23.7 | 59.7 | 90 | + | 4 | 12 |
| 30. * | 20 " " | 1437 | 1623 | " | 25.6 | 64.4 | 105 | 0 | 4 | 16 |
| 31. | 19 May 1970 | 1800 | ---- | (pre-Alma) | 15.0 | 82.5 | 35 | ++ | 5 | 4 |
| 32. | 20 " " | 1440 | 1722 | ALMA | 17.3 | 81.5 | 65 | 0 | 1,5 | 13 |
| 33. | 22 " " | 1410 | 1624 | " | 19.0 | 82.0 | 30 | 0 | 1,5 | 9 |
| 34. | 23 " " | 1200 | ---- | " | 21.0 | 83.7 | 30 | 0 | 5 | 4 |
| 35. | 24 " " | 0000 | ---- | " | 22.8 | 84.0 | 30 | 0 | 5 | 4 |
| 36. | 18 July 1970 | 1416 | 1955 | (pre-Becky) | 19.6 | 83.7 | 25 | 0 | 1 | 12 |
| 37. | 19 " " | 1405 | 1945 | " " | 21.4 | 86.2 | 30 | + | 1,5 | 16 |
| 38. | 20 " " | 1407 | 1710 | BECKY | 24.3 | 87.5 | 50 | 0 | 1,5 | 12 |
| 39. | 21 " " | 1402 | 1735 | " | 27.2 | 86.4 | 55 | - | 1 | 14 |
| 40. | 31 July 1970 | 1200 | ---- | (pre-Celia) | 20.5 | 83.3 | 25 | + | 5 | 4 |
| 41. | 01 Aug. " | 0000 | ---- | " " | 22.0 | 84.5 | 35 | + | 5 | 4 |
| 42. * | 02 " " | 1526 | 1652 | CELIA | 25.5 | 90.2 | 100 | 0 | 4,5 | 14 |
| 43. * | 03 " " | 1530 | 1657 | " | 27.5 | 96.3 | 110 | ++ | 4 | 12 |
| 44. | 08 Sept.1971 | 1559 | 1841 | EDITH | 14.0 | 77.5 | 80 | ++ | 1,5 | 15 |

Table 5.--(continued).

| Case* no. | Date | Time (GMT) bgng. | end | Storm name | Location lat. (°N) | long. (°W) | MWS (kt) | Change | Vectors source | no. |
|---|---|---|---|---|---|---|---|---|---|---|
| 45. | 09 Sept. 1971 | 1313 | 1554 | EDITH | 15.0 | 82.5 | 120 | ++ | 1 | 9 |
| 46. | 09 " " | 1500 | 1742 | " | 15.0 | 82.5 | 140 | ++ | 1,5 | 10 |
| 47. | 08 Sept. 1971 | 1559 | 1841 | FERN | 26.5 | 93.0 | 70 | + | 1,5 | 14 |
| 48. | 09 Sept. 1971 | 1313 | 1554 | (pre-Ginger) | 27.5 | 67.0 | 30 | + | 1,5 | 7 |
| 49. | 09 " " | 1500 | 1742 | " " | 27.5 | 67.0 | 35 | + | 1 | 10 |
| 50. | 11 " " | 1209 | 1423 | GINGER | 28.0 | 63.0 | 65 | + | 1,5 | 12 |
| 51. | 11 " " | 1423 | 1657 | " | 28.0 | 62.5 | 65 | + | 1,5 | 14 |
| 52. | 12 " " | 1435 | 1650 | " | 30.7 | 59.0 | 75 | + | 1 | 14 |
| 53. | 14 " " | 1606 | 1849 | " | 33.5 | 49.5 | 80 | - | 1 | 13 |
| 54. | 12 Sept. 1971 | 1435 | 1650 | HEIDI | 31.0 | 73.0 | 40 | + | 1 | 6 |
| 55. * | 15 June 1972 | 1301 | 1449 | (pre-Agnes) | 20.0 | 85.0 | 25 | + | 1,5 | 16 |
| 56. * | 16 " " | 1451 | 1706 | AGNES | 20.5 | 85.5 | 40 | + | 1,5 | 13 |
| 57. * | 17 " " | 1519 | 1734 | " | 21.5 | 85.3 | 55 | + | 1,5 | 19 |
| 58. * | 18 " " | 1448 | 1703 | " | 24.5 | 85.5 | 70 | + | 1,5 | 14 |
| 59. * | 19 " " | 1310 | 1525 | " | 29.0 | 86.0 | 65 | - | 1,5 | 13 |
| 60. * | 17 June 1972 | 1519 | 1734 | (unnamed) | 27.0 | 67.5 | 35 | 0 | 1 | 16 |
| 61. * | 18 " " | 1448 | 1703 | " | 28.0 | 68.0 | 35 | 0 | 1 | 15 |
| 62. * | 19 " " | 1310 | 1525 | " | 30.0 | 67.0 | 30 | 0 | 1 | 15 |
| 63. * | 20 " " | 1522 | 1736 | " | 32.0 | 65.0 | 25 | - | 1 | 13 |
| 64. | 25 Aug. 1972 | 1220 | 1959 | BETTY | 37.5 | 53.0 | 50 | 0 | 1 | 5 |
| 65. | 26 " " | 1331 | 1519 | " | 38.0 | 50.5 | 55 | + | 1 | 6 |
| 66. | 29 " " | 1303 | 1518 | " | 41.0 | 33.5 | 70 | - | 1 | 11 |
| 67. | 29 Aug. 1972 | 1303 | 1518 | (unnamed) | 16.0 | 34.0 | 25 | 0 | 1 | 13 |
| 68. | 06 Sept. 1972 | 1428 | 1644 | DAWN | 28.0 | 76.0 | 50 | + | 1,5 | 25 |
| 69. | 07 " " | 1454 | 1642 | " | 33.5 | 71.0 | 65 | 0 | 1,5 | 11 |
| 70. | 08 " " | 1428 | 1643 | " | 36.3 | 73.7 | 65 | - | 1 | 15 |
| 71. | 09 " " | 1418 | 1633 | " | 34.5 | 73.5 | 50 | - | 1,5 | 12 |
| 72. | 03 June 1973 | 1734 | 1923 | AVA | 13.2 | 97.2 | 60 | + | 1 | 10 |
| 73. | 04 " " | 1651 | 1839 | " | 13.5 | 100.0 | 75 | 0 | 1 | 12 |
| 74. * | 06 " " | 1703 | 1852 | " | 12.6 | 109.7 | 130 | + | 1 | 14 |
| 75. | 29 June 1973 | 1640 | 1855 | (pre-Alice) | 27.5 | 71.2 | 25 | 0 | 1 | 14 |
| 76. | 30 " " | 1724 | 1912 | " " | 26.8 | 70.0 | 25 | 0 | 1 | 12 |
| 77. | 01 July " | 1700 | 1849 | ALICE | 26.5 | 68.2 | 30 | 0 | 1 | 11 |
| 78. | 03 " " | 1250 | 1439 | " | 30.5 | 65.0 | 60 | + | 1,5 | 12 |
| 79. * | 15 Aug. 1973 | 1329 | 1514 | (pre-Brenda) | 16.0 | 69.5 | 20 | 0 | 1 | 15 |
| 80. * | 15 " " | 1710 | 1900 | " " | 15.8 | 70.3 | 20 | 0 | 1 | 19 |
| 81. * | 16 " " | 1354 | 1543 | " " | 17.1 | 74.6 | 20 | 0 | 1 | 13 |
| 82. * | 16 " " | 1711 | 1903 | " " | 17.5 | 75.0 | 20 | 0 | 1 | 15 |
| 83. * | 17 " " | 1320 | 1536 | BRENDA | 18.4 | 79.6 | 20 | 0 | 1 | 16 |
| 84. * | 17 " " | 1700 | 1852 | " | 19.0 | 80.4 | 25 | + | 1 | 13 |
| 85. * | 18 " " | 1349 | 1537 | " | 21.4 | 85.0 | 35 | ++ | 1 | 12 |
| 86. * | 18 " " | 1655 | 1847 | " | 21.4 | 85.0 | 40 | ++ | 1 | 17 |
| 87. * | 20 " " | 1343 | 1532 | " | 20.1 | 90.6 | 55 | + | 1 | 14 |
| 88. * | 20 " " | 1705 | 1905 | " | 20.3 | 91.3 | 60 | + | 1 | 17 |

*Denotes good case, for which picture registration and the number and distribution of high-cloud vectors is judged to be better than average.

Table 5.--(continued).

Notes to table 5.

MWS is the mean maximum surface or low-level wind speed, in knots (used as the measure of storm intensity).

Change is the change in MWS observed or estimated to have been occurring at picture time, according to the following scale:

- \- = weakening by more than 10 kt/24 hr.
- 0 = little change ($\leq$ 10 kt/24 hr).
- \+ = intensifying (+11 to +25 kt/24 hr).
- ++ = strongly intensifying ($>$+25 kt/24 hr).

Source of vectors:

1 = NESS film loops.
2 = Film loops obtained from T. T. Fujita.
3 = The Electronic Animation System in the Meteorological Satellite Laboratory, NESS.
4 = Vector sets derived by other researchers (Timchalk NESS, unpublished, Smith 1972, Fujita and Black 1970).
5 = 200-mb rawinsonde data (150-mb rawinsonde data for some days of hurricane Camille).

If rawinsonde data were combined with cloud vectors whose times averaged more than four hours from the nearest synoptic hour (1200 or 0000 GMT), the rawinsonde data were interpolated in time.

Table 6.--Measures of "goodness of fit" of the polynomial equations and values of numerically calculated basic parameters, for the 88 acceptable cases.

| Case* no. | Polynomial "fit": Number of vectors | Degree | RMSE u | RMSE v | Embedded distance | Parameters calculated from polynomial equations: Mean div | Mean vort. | Div | Vort. | Wind | Storm track | Vert. shear |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | 7 | 2 | .08 | 1.29 | 1.0 | 1.4 | -1.9 | 2.2 | 0.8 | 325/10 | 170/07 | 335/17 |
| 2. | 7 | 3 | .01 | .01 | 1.5 | 1.4 | -2.2 | 4.4 | -1.9 | 353/05 | 180/08 | 357/13 |
| 3. | 7 | 3 | .05 | .04 | 1.5 | 1.1 | -1.8 | 1.5 | -0.8 | 153/09 | 200/10 | 076/07 |
| 4. | 7 | 3 | .01 | .06 | 1.5 | 1.4 | -2.4 | 2.7 | -7.5 | 198/42 | 195/05 | 199/37 |
| 5. | 8 | 2 | 5.88 | 4.20 | 2.5 | 0.5 | -1.8 | 1.9 | -3.0 | 206/21 | 200/07 | 209/14 |
| 6. | 8 | 2 | 2.20 | 2.53 | 2.0 | 0.2 | -0.3 | 1.7 | -0.5 | 266/22 | 260/03 | 267/19 |
| 7. * | 25 | 3 | 3.80 | 4.44 | 0.5 | 3.5 | -4.8 | 2.5 | -9.1 | 214/28 | 275/08 | 198/25 |
| 8. * | 25 | 3 | 3.71 | 3.65 | 0.5 | 1.9 | -5.5 | 1.0 | -7.0 | 226/28 | 272/08 | 211/23 |
| 9. * | 25 | 3 | 4.47 | 4.08 | 1.0 | 2.7 | -5.1 | 6.1 | -4.3 | 186/31 | 270/07 | 173/31 |
| 10. * | 14 | 3 | 4.85 | 3.05 | 3.5 | 0.4 | -2.0 | 1.2 | -4.2 | 317/01 | 180/05 | 351/06 |
| 11. * | 21 | 3 | 3.15 | 2.24 | 1.5 | 2.5 | -4.1 | 4.8 | -4.4 | 265/03 | 180/14 | 346/14 |
| 12. * | 25 | 3 | 4.17 | 2.74 | 1.0 | 2.4 | -4.4 | 3.7 | -7.5 | 290/11 | 180/15 | 331/21 |
| 13. * | 25 | 3 | 4.18 | 2.90 | 1.5 | 2.5 | -4.2 | 4.3 | -5.1 | 209/18 | 180/15 | 263/09 |
| 14. * | 25 | 3 | 5.33 | 3.61 | 1.5 | 3.3 | -4.8 | 4.5 | -5.7 | 186/32 | 165/18 | 209/16 |
| 15. * | 25 | 3 | 4.60 | 4.09 | 1.5 | 3.0 | -6.1 | 5.9 | -4.1 | 198/32 | 165/18 | 228/20 |
| 16. | 13 | 3 | 1.03 | 2.62 | 2.0 | 3.4 | -3.9 | 2.4 | -4.0 | 281/44 | 248/19 | 301/30 |
| 17. | 10 | 3 | 1.67 | 4.06 | 5.0 | 0.8 | -1.6 | -0.5 | -2.7 | 111/12 | 098/12 | 202/03 |
| 18. | 12 | 3 | 1.63 | 1.86 | 1.0 | 1.3 | -0.2 | 0.6 | -2.4 | 176/12 | 105/12 | 231/14 |
| 19. | 7 | 2 | 1.42 | 7.44 | 3.5 | 0.8 | -1.4 | 2.1 | -1.4 | 173/13 | 118/11 | 228/11 |
| 20. | 12 | 2 | 6.32 | 5.62 | 4.0 | 2.2 | -1.4 | 1.9 | -2.4 | 127/05 | 132/09 | 317/04 |
| 21. | 8 | 3 | .01 | .05 | 2.5 | 1.6 | -3.0 | 1.4 | -0.1 | 314/14 | 145/08 | 318/22 |
| 22. | 14 | 2 | 4.03 | 12.55 | 4.0 | 1.6 | -1.0 | 1.9 | -1.5 | 192/09 | 153/09 | 265/06 |
| 23. | 13 | 2 | 6.08 | 5.81 | 4.5 | 1.3 | -1.5 | 0.2 | -2.8 | 339/15 | 140/10 | 332/24 |
| 24. | 12 | 2 | 6.09 | 2.96 | 4.0 | 1.5 | -1.7 | 1.7 | -2.4 | 278/07 | 150/11 | 310/17 |
| 25. | 12 | 3 | 1.49 | .65 | 3.5 | 0.6 | -2.7 | 2.5 | -0.6 | 237/11 | 160/13 | 294/15 |
| 26. | 12 | 3 | 2.29 | 1.64 | 1.0 | 4.3 | -1.3 | 5.2 | 1.1 | 098/03 | 132/11 | 323/09 |
| 27. | 15 | 3 | 3.96 | 2.51 | 1.0 | 2.6 | -0.7 | 6.0 | -1.0 | 103/07 | 130/11 | 340/06 |
| 28. | 12 | 3 | 2.57 | 3.28 | 4.0 | 1.3 | -1.1 | 1.7 | 1.5 | 142/06 | 125/13 | 291/07 |
| 29. | 12 | 3 | 4.37 | 4.91 | 3.0 | 1.8 | -1.1 | 3.1 | 0.6 | 147/15 | 120/14 | 214/07 |
| 30. * | 16 | 2 | 4.06 | 3.63 | 2.5 | 4.4 | -4.5 | 4.6 | -3.2 | 160/07 | 130/12 | 282/07 |
| 31. | 4 | 1 | .66 | .44 | 0.5 | 2.4 | -2.2 | 4.6 | -0.1 | 140/18 | 165/07 | 126/12 |
| 32. | 13 | 3 | 1.45 | 6.46 | 3.5 | 1.3 | -3.2 | 4.5 | -3.4 | 168/21 | 215/07 | 151/17 |
| 33. | 9 | 2 | 4.29 | 4.81 | 1.5 | 0.8 | -3.6 | 0.1 | -3.2 | 225/37 | 075/06 | 229/43 |
| 34. | 4 | 1 | .40 | .07 | 1.5 | 0.6 | -2.3 | -0.2 | -2.7 | 234/49 | 160/10 | 246/47 |
| 35. | 4 | 1 | 1.46 | .16 | 0.5 | -0.8 | 0.7 | 0.8 | -0.8 | 238/48 | 180/12 | 252/43 |
| 36. | 12 | 3 | .96 | 2.04 | 2.0 | 0.7 | -2.4 | 2.4 | -4.9 | 158/11 | 110/08 | 204/08 |
| 37. | 16 | 3 | 2.11 | 3.19 | 2.0 | 0.9 | -3.9 | 2.8 | -2.4 | 212/31 | 150/09 | 228/28 |
| 38. | 12 | 2 | 4.34 | 9.25 | 4.0 | 0.9 | -0.7 | 2.4 | -1.4 | 241/11 | 165/10 | 290/13 |
| 39. | 14 | 3 | 3.02 | 4.61 | 1.5 | 0.9 | -1.6 | 3.2 | -1.4 | 249/18 | 195/09 | 278/15 |
| 40. | 4 | 1 | .21 | .00 | 2.0 | -0.1 | -0.2 | 0.1 | 0.7 | 199/06 | 150/09 | 291/07 |
| 41. | 4 | 0 | .32 | .32 | 1.0 | 2.0 | -1.2 | 1.9 | -1.3 | 045/05 | 142/09 | 348/11 |
| 42. * | 14 | 2 | 4.63 | 6.70 | 2.5 | 2.3 | -2.0 | 2.4 | -2.6 | 120/25 | 110/12 | 129/13 |
| 43. * | 12 | 3 | 5.74 | 1.84 | 3.0 | 3.9 | -3.4 | 6.1 | -0.6 | 089/13 | 115/14 | 001/06 |

Table 6.--(continued).

| Case* no. | Polynomial "fit": Number of vectors | Degree | RMSE u | RMSE v | Embedded Distance | Parameters calculated from polynomial equations: Mean div. | Mean vort. | Div. | Vort. | Wind | Storm track | Vert. shear |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 44. | 15 | 2 | 7.65 | 4.83 | 2.0 | 1.7 | -2.0 | 3.0 | -2.1 | 064/19 | 100/16 | 008/11 |
| 45. | 9 | 3 | .06 | .01 | 1.0 | 1.2 | -2.5 | 5.2 | 7.1 | 062/24 | 105/15 | 023/17 |
| 46. | 10 | 2 | 6.34 | 3.04 | 2.5 | 1.4 | 0.0 | 1.9 | 1.1 | 034/18 | 110/15 | 348/20 |
| 47. | 14 | 2 | 6.84 | 9.60 | 1.5 | 4.2 | -1.5 | 2.3 | -0.4 | 343/13 | 090/03 | 331/14 |
| 48. | 7 | 3 | .00 | .01 | 3.0 | -0.2 | -0.6 | 0.8 | 2.5 | 285/42 | 220/03 | 288/41 |
| 49. | 10 | 3 | .03 | .00 | 1.5 | 2.6 | -4.4 | 4.8 | -1.9 | 278/67 | 225/04 | 281/64 |
| 50. | 12 | 2 | 3.01 | 6.98 | 1.0 | 1.9 | -1.6 | 3.6 | 0.2 | 014/04 | 250/09 | 054/12 |
| 51. | 14 | 3 | 2.77 | 3.58 | 3.0 | 2.6 | -2.8 | 3.8 | -0.7 | 224/32 | 245/10 | 215/23 |
| 52. | 14 | 2 | 6.71 | 6.67 | 3.0 | 3.0 | -3.7 | 3.2 | -3.2 | 296/07 | 225/10 | 004/10 |
| 53. | 13 | 3 | 4.58 | 1.56 | 0.5 | 3.3 | -2.2 | -5.1 | -5.5 | 291/16 | 270/08 | 309/09 |
| 54. | 6 | 2 | .02 | .01 | 1.5 | 4.3 | -2.5 | 5.4 | -0.1 | 267/24 | 200/09 | 289/22 |
| 55. * | 16 | 3 | 4.78 | 3.18 | 2.0 | 1.8 | -2.0 | 4.6 | -3.2 | 297/23 | 270/03 | 300/21 |
| 56. * | 13 | 2 | 4.16 | 5.92 | 2.0 | 2.8 | -2.2 | 3.1 | -3.6 | 272/12 | 230/04 | 289/09 |
| 57. * | 19 | 2 | 5.63 | 8.80 | 3.5 | 2.0 | -3.0 | 3.6 | -1.4 | 222/20 | 175/06 | 237/17 |
| 58. * | 14 | 2 | 8.51 | 3.18 | 2.0 | 1.0 | -2.3 | 1.2 | -0.3 | 216/19 | 175/09 | 241/13 |
| 59. * | 13 | 3 | 3.06 | 4.26 | 1.5 | 2.6 | -1.6 | 0.2 | -2.5 | 140/14 | 185/12 | 084/10 |
| 60. * | 16 | 3 | 4.45 | 4.57 | 4.0 | 1.0 | -1.9 | 3.7 | -1.7 | 247/46 | 150/02 | 250/46 |
| 61. * | 15 | 3 | 4.70 | 4.51 | 6.0 | 1.2 | -1.2 | 1.3 | -0.3 | 260/24 | 180/03 | 267/24 |
| 62. * | 15 | 3 | 3.88 | 4.11 | 5.0 | 1.2 | -0.8 | 1.7 | -1.1 | 321/26 | 210/05 | 331/28 |
| 63. * | 13 | 3 | 3.03 | 6.41 | 5.0 | 0.7 | -0.5 | 3.2 | 2.3 | 290/44 | 220/06 | 298/43 |
| 64. | 5 | 2 | .00 | .00 | 0.5 | 2.8 | -5.2 | 3.2 | -4.0 | 343/21 | 255/03 | 351/21 |
| 65. | 6 | 1 | 3.59 | 5.89 | 2.0 | 3.5 | -2.8 | 7.6 | -3.7 | 301/22 | 240/05 | 314/20 |
| 66. | 11 | 2 | 1.86 | 6.14 | 1.0 | 1.0 | -1.7 | 0.8 | -5.6 | 303/26 | 270/03 | 307/24 |
| 67. | 13 | 2 | 12.28 | 6.55 | 6.0 | 1.4 | -2.7 | -0.1 | -3.3 | 157/23 | 090/20 | 207/24 |
| 68. | 25 | 3 | 4.11 | 6.26 | 4.5 | 1.3 | -2.8 | 1.6 | -4.0 | 235/26 | 240/14 | 229/12 |
| 69. | 11 | 1 | 18.37 | 17.40 | 2.5 | 1.6 | -3.2 | 1.4 | 0.5 | 277/34 | 205/18 | 308/33 |
| 70. | 15 | 3 | 6.78 | 2.99 | 0.5 | 1.1 | -3.2 | 1.8 | -4.7 | 243/44 | 105/07 | 248/50 |
| 71. | 12 | 1 | 9.33 | 6.83 | 1.0 | 1.7 | -0.7 | 4.3 | 0.4 | 352/05 | 315/08 | 095/05 |
| 72. | 10 | 2 | 1.64 | 6.41 | 1.0 | 4.7 | -1.2 | 6.6 | 2.5 | 176/11 | 095/07 | 210/12 |
| 73. | 12 | 3 | 1.06 | 2.64 | 2.0 | 3.2 | -2.1 | 4.1 | -2.5 | 128/24 | 095/08 | 142/18 |
| 74. * | 14 | 3 | 2.11 | 3.03 | 3.0 | 3.0 | -0.8 | 7.1 | -1.0 | 336/06 | 090/12 | 291/16 |
| 75. | 14 | 3 | 2.86 | 2.00 | 3.0 | 0.8 | -3.0 | 1.7 | -3.0 | 256/32 | 270/03 | 255/29 |
| 76. | 12 | 3 | 1.19 | 1.42 | 0.5 | 0.8 | -3.3 | 3.2 | 6.3 | 153/10 | 270/03 | 140/12 |
| 77. | 11 | 2 | 3.34 | 4.69 | 0.5 | 1.0 | -2.5 | 1.0 | -1.5 | 253/32 | 240/04 | 255/28 |
| 78. | 12 | 2 | 4.71 | 4.28 | 2.0 | 4.7 | -1.0 | 4.9 | 1.2 | 195/20 | 190/08 | 199/12 |
| 79. * | 15 | 2 | 7.12 | 4.26 | 1.0 | 0.6 | -3.8 | 3.1 | -2.4 | 179/23 | 090/10 | 203/24 |
| 80. * | 19 | 3 | 3.05 | 2.49 | 2.5 | 1.4 | -2.8 | 3.9 | -0.5 | 223/16 | 090/10 | 240/24 |
| 81. * | 13 | 3 | 4.25 | 3.53 | 1.0 | 1.0 | -3.4 | 5.0 | -4.2 | 183/18 | 095/12 | 218/21 |
| 82. * | 15 | 3 | 4.64 | 3.10 | 2.5 | 1.7 | -3.1 | 5.3 | -2.3 | 202/20 | 100/13 | 231/26 |
| 83. * | 16 | 3 | 1.53 | 3.95 | 1.5 | 2.6 | -1.7 | 5.3 | -4.6 | 305/03 | 120/12 | 301/15 |
| 84. * | 13 | 2 | 6.92 | 5.27 | 2.5 | 2.2 | -4.6 | 3.3 | -5.2 | 141/09 | 120/09 | 262/05 |
| 85. * | 12 | 2 | 3.70 | 4.75 | 2.0 | 2.4 | -3.1 | 3.8 | -5.3 | 283/07 | 105/10 | 284/17 |
| 86. * | 17 | 2 | 6.27 | 6.76 | 2.5 | 3.3 | -4.1 | 4.0 | -4.3 | 152/13 | 105/10 | 202/10 |
| 87. * | 14 | 3 | 2.59 | 2.82 | 1.5 | 0.9 | -2.4 | 2.9 | -5.2 | 298/04 | 050/05 | 260/08 |
| 88. * | 17 | 3 | 3.86 | 3.94 | 3.0 | 0.3 | -2.5 | 0.5 | -1.6 | 281/43 | 050/05 | 277/47 |

Table 6.--(continued).

---

Notes to table 6.

The columns headed Case no. and Number of vectors are identical with the extreme left and extreme right-hand columns, respectively, of table 5. An asterisk (8) denotes "good" case, for which picture registration and the number and distribution of high-cloud vectors is judged to be better than average.

Degree is the degree of polynomial equation used to fit the u and v components of the high-level vector input data:

0 = plane fit (3 variables: $x$, $y$, constant).
1 = four variables ($xy$, $x$, $y$, constant).
2 = second-degree polynomial (6 variables).
3 = third-degree polynomial (10 variables).

RMSE is the root-mean-square error (kt) by which the polynomial solution differs from the observed input data. Solutions are calculated separately for u and v components.

Embedded distance is the embedded distance (to the nearest one-half degree of latitude) of the storm or disturbance center within the perimeter of the high-level vector field. (The perimeter is defined by straight-line connections between the outermost vectors).

Mean div. is the horizontal divergence ($10^{-5}s^{-1}$) calculated from plane fit at the center of the grid area.

Mean vort. is the relative vorticity ($10^{-5}s^{-1}$) calculated from plane fit at the center of the grid area.

Div, vort., Wind are the horizontal divergence and relative vorticity ($10^{-5}s^{-1}$), and wind direction and speed, respectively, calculated from the polynomial solutions at the location of the storm center. Wind is given in degrees and knots.

Storm track is the direction (degrees) and speed (kt) from which the storm or disturbance center was moving at picture time. This parameter is used as input data.

Vert. shear is the vertical wind shear (degrees/kt), calculated as the vector difference between the observed storm track and the calculated high-level wind over the storm center.

Table 7.--Numerically calculated estimates of 7 parameters for 32 "good" cases.

| | Case no. | MWS (kt) | Change | Degree | Mean div. | Mean vort. | Div. | Vort. | Vert. shear | MDiv / shear | MD × S (0) / shear |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Parameters | | | | |
| 1. | 7 | 45 | + | 3 | 3.5 | -4.8 | 2.5 | -9.1 | 25 | .14 | 2.74 |
| 2. | 8 | 50 | + | 3 | 1.9 | -5.5 | 1.0 | -7.0 | 23 | .08 | 2.77 |
| 3. | 9 | 55 | + | 3 | 2.7 | -5.1 | 6.1 | -4.3 | 31 | .09 | 2.26 |
| 4. | 10 | 20 | + | 3 | 0.4 | -2.0 | 1.2 | -4.2 | 6 | .07 | .64 |
| 5. | 11 | 30 | + | 3 | 2.5 | -4.1 | 4.8 | -4.4 | 14 | .18 | 2.18 |
| 6. | 12 | 32 | + | 3 | 2.4 | -4.4 | 3.7 | -7.5 | 21 | .11 | 1.26 |
| 7. | 13 | 35 | + | 3 | 2.5 | -4.2 | 4.3 | -5.1 | 9 | .28 | 2.36 |
| 8. | 14 | 45 | + | 3 | 3.3 | -4.8 | 4.5 | -5.7 | 16 | .20 | 2.33 |
| 9. | 15 | 50 | + | 3 | 3.0 | -6.1 | 5.9 | -4.1 | 20 | .15 | 3.12 |
| 10. | 30 | 105 | 0 | (3) | 4.4 | -4.5 | (7.9) | (-2.5) | ( 5) | (.88) | (4.05) |
| | | | | 2 | | | 4.6 | -3.2 | 7 | .61 | 2.81 |
| 11. | 42 | 100 | 0 | (3) | 2.3 | -2.0 | (5.4) | (-3.8) | ( 9) | (.26) | (1.07) |
| | | | | 2 | | | 2.4 | -2.6 | 13 | .18 | .74 |
| 12. | 43 | 110 | ++ | 3 | 3.9 | -3.4 | 6.1 | -0.6 | 6 | .64 | 5.50 |
| 13. | 55 | 25 | + | 3 | 1.8 | -2.0 | 4.6 | -3.2 | 21 | .09 | 1.17 |
| 14. | 56 | 40 | + | (3) | 2.8 | -2.2 | (-1.6) | (-1.6) | (10) | (.29) | (1.59) |
| | | | | 2 | | | 3.1 | -3.6 | 9 | .30 | 1.64 |
| 15. | 57 | 55 | + | (3) | 2.0 | -3.0 | (5.3) | (-3.2) | (32) | (.06) | (1.07) |
| | | | | 2 | | | 3.6 | -1.4 | 17 | .12 | 2.08 |
| 16. | 58 | 70 | + | (3) | 1.0 | -2.3 | (6.1) | (-2.6) | (17) | (.06) | (1.11) |
| | | | | 2 | | | 1.2 | -0.3 | 13 | .07 | 1.40 |
| 17. | 59 | 65 | - | 3 | 2.6 | -1.6 | 0.2 | -2.5 | 10 | .25 | 1.53 |
| 18. | 60 | 35 | 0 | 3 | 1.0 | -1.9 | 3.7 | -1.7 | 46 | .02 | .93 |
| 19. | 61 | 35 | 0 | 3 | 1.2 | -1.2 | 1.3 | -0.3 | 24 | .05 | 1.45 |
| 20. | 62 | 30 | 0 | 3 | 1.2 | -0.8 | 1.7 | -1.1 | 28 | .04 | 1.01 |
| 21. | 63 | 25 | - | 3 | 0.7 | -0.5 | 3.2 | -2.3 | 43 | .02 | .59 |
| 22. | 74 | 130 | + | 3 | 3.0 | -0.8 | 7.1 | -1.0 | 16 | .19 | 6.97 |
| 23. | 79 | 20 | 0 | (3) | 0.6 | -3.8 | (3.5) | (-6.7) | (29) | (.02) | ( .67) |
| | | | | 2 | | | 3.1 | -2.4 | 24 | .02 | .79 |
| 24. | 80 | 20 | 0 | 3 | 1.4 | -2.8 | 3.9 | -0.5 | 24 | .06 | 1.87 |
| 25. | 81 | 20 | 0 | 3 | 1.0 | -3.4 | 5.0 | -4.2 | 21 | .05 | 1.16 |
| 26. | 82 | 20 | 0 | 3 | 1.7 | -3.1 | 5.3 | -3.2 | 26 | .07 | .78 |
| 27. | 83 | 20 | 0 | 3 | 2.6 | -1.7 | 5.3 | -4.6 | 15 | .17 | 2.14 |
| 28. | 84 | 25 | + | (3) | 2.2 | -4.6 | (4.5) | (-1.6) | (16) | (.14) | ( .71) |
| | | | | 2 | | | 3.3 | -5.2 | 5 | .43 | 2.16 |
| 29. | 85 | 35 | ++ | (3) | 2.4 | -3.1 | (8.1) | (-10.8) | (44) | (.05) | ( .62) |
| | | | | 2 | | | 3.8 | -5.3 | 17 | .14 | 1.62 |
| 30. | 86 | 40 | ++ | (3) | 3.3 | -4.1 | (7.2) | (-4.4) | ( 8) | (.39) | (2.76) |
| | | | | 2 | | | 4.0 | -4.0 | 10 | .34 | 2.44 |
| 31. | 87 | 55 | + | 3 | 0.9 | -2.4 | 2.9 | -5.2 | 8 | .12 | .72 |
| 32. | 88 | 60 | + | 3 | 0.3 | -2.5 | 0.5 | -1.6 | 47 | .01 | .13 |

Table 7.--(continued).

Notes to table 7.

Definitions of all parameters except the two right-hand ones appear in the notes to tables 5 and 6.

$\frac{\text{MDiv}}{\text{Shear}}$ is the Mean Divergence (calculated from plane fit at the center of the grid area) divided by the speed of the vertical shear. The quantity has dimensions of $10^{-5}s^{-1}/kt$.

$\frac{\text{MD} \times \text{S(0)}}{\text{Shear}}$ is the Mean Divergence multiplied by the ratio: plane-fit vertical shear/polynomial-fit vertical shear. The quantity has dimensions of $10^{-5}s^{-1}$.

Tabulated items within parentheses are derived from third-degree polynomial solutions rejected by the computer. Rejection may or may not have been warranted.

(Continued from inside front cover)

NESS 36 A Technique for the Analysis and Forecasting of Tropical Cyclone Intensities From Satellite Pictures. Vernon F. Dvorak, June 1972. (COM-72-10840)

NESS 37 Some Preliminary Results of 1971 Aircraft Microwave Measurements of Ice in the Beaufort Sea. Richard J. DeRycke and Alan E. Strong, June 1972. (COM-72-10847)

NESS 38 Publications and Final Reports on Contracts and Grants, 1971--NESS. June 1972. (COM-72-11115)

NESS 39 Operational Procedures for Estimating Wind Vectors From Geostationary Satellite Data. Michael T. Young, Russell C. Doolittle, and Lee M. Mace, July 1972. (COM-72-10910)

NESS 40 Convective Clouds as Tracers of Air Motion. Lester F. Hubert and Andrew Timchalk, August 1972. (COM-72-11421)

NESS 41 Effect of Orbital Inclination and Spin Axis Attitude on Wind Estimates From Photographs by Geosynchronous Satellites. Linwood F. Whitney, Jr., September 1972. (COM-72-11499)

NESS 42 Evaluation of a Technique for the Analysis and Forecasting of Tropical Cyclone Intensities From Satellite Pictures. Carl O. Erickson, September 1972. (COM-72-11472)

NESS 43 Cloud Motions in Baroclinic Zones. Linwood F. Whitney, Jr., October 1972. (COM-73-10029)

NESS 44 Estimation of Average Daily Rainfall From Satellite Cloud Photographs. Walton A. Follansbee, January 1973. (COM-73-10539)

NESS 45 A Technique for the Analysis and Forecasting of Tropical Cyclone Intensities From Satellite Pictures. (Revision of NESS 36) Vernon F. Dvorak, February 1973. (COM-73-10675)

NESS 46 Publications and Final Reports on Contracts and Grants, 1972--NESS. April 1973.

NESS 47 Stratospheric Photochemistry of Ozone and SST Pollution: An Introduction and Survey of Selected Developments Since 1965. Martin S. Longmire, March 1973. (COM-73-10786)

NESS 48 Review of Satellite Measurements of Albedo and Outgoing Long-Wave Radiation. Arnold Gruber, July 1973. (COM-73-11443)

NESS 49 Operational Processing of Solar Proton Monitor Data. Louis Rubin, Henry L. Phillips, and Stanley R. Brown, August 1973. (COM-73-11647-AS)

NESS 50 An Examination of Tropical Cloud Clusters Using Simultaneously Observed Brightness and High Resolution Infrared Data From Satellites. Arnold Gruber, September 1973. (COM-73-11941/4AS)

NESS 51 SKYLAB Earth Resources Experiment Package Experiments in Oceanography and Marine Science. A. L. Grabham and John W. Sherman, III, September 1973.

NESS 52 Operational Products From ITOS Scanning Radiometer Data. Edward F. Conlan, October 1973. (COM-74-10040)

NESS 53 Catalog of Operational Satellite Products. Eugene R. Hoppe and Abraham L. Ruiz (Editors). March, 1974. (COM-74-11339/AS)

NESS 54 A Method of Converting the SMS/GOES WEFAX Frequency (1691 MHz) to the Existing APT/WEFAX Frequency (137 MHz). John J. Nagle, April 1974.

NESS 55 Publications and Final Reports on Contracts and Grants, 1973 - NESS. April, 1974.

NESS 56 What Are You Looking at When You Say This Area Is a Suspect Area for Severe Weather? Arthur H. Smith, Jr., February 1974. (COM-74-11333/AS)

NESS 57 Nimbus-5 Sounder Data Processing System, Part I: Measurement Characteristics and Data Reduction Procedures. W. L. Smith, H. M. Woolf, P. G. Abel, C. M. Hayden, M. Chalfant, and N. Grody, in press, 1974.

NESS 58 The Role of Satellites in Snow and Ice Measurements. Donald R. Wiesnet, in press, 1974.