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by G. Jager.

NATIONAL ENVIRONMENTAL SATELLITE CENTER
Washington, D.C.

October 1968

Operational Utilization of Upper Tropospheric Wind Estimates Based on Meteorological Satellite Photographs

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Technical Memorandum NESCTM 8

U.S. DEPARTMENT OF COMMERCE / ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

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51 places
of which 14 are punctuation

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3 colons
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OPERATIONAL UTILIZATION OF UPPER TROPOSPHERIC WIND ESTIMATES BASED ON METEOROLOGICAL SATELLITE PHOTOGRAPHS

Gilbert Jager, Walton A. Follansbee, and Vincent J. Oliver
Applications Group, Office of Operations

WASHINGTON, D.C.
October 1968

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ABSTRACT

A technique of estimating upper tropospheric winds over the tropics and subtropics utilizing the appearance of cirriform clouds in meteorological satellite photographs is described. Specifically, the appearance of cirrus cumulonimbogenitus, cirrus spissatus, and the edges of cirrostratus shields is used to furnish clues to the wind direction and speed in their immediate proximity. Known relationships are used to estimate large-scale wind flow at the 200 and 300 millibar levels of the atmosphere. The National Meteorological Center now routinely incorporates such wind estimates into operational numerical map analyses. The data are also transmitted in both analog and digital form to a number of weather centers for use in both conventional and numerical analyses. An objective method for verifying these wind estimates is described, and the results of a six-month test of the data are given.

I. INTRODUCTION

Since the advent of weather satellites in 1960, one of the primary goals of the National Environmental Satellite Center (NESC) has been to incorporate the data into operational analyses. Most studies to date have been concerned with synoptic scale cloud formations associated with individual atmospheric disturbances. While studies of this type increase our ability to infer certain relationships between satellite-pictured cloud patterns and meteorological parameters, such inferences have, to date, been qualitative rather than quantitative.

The procedure described herein is one of the first in which an attempt has been made to derive quantitative information directly from satellite cloud pictures. Wind information is extracted from the cloud data in the form of estimates of wind directions and speeds at specific locations. Such estimates, confined to tropical and subtropical areas, are now being used operationally in both objective and subjective analyses.

When the National Meteorological Center initiated an operational tropical analysis program, the lack of high level wind data over much of the area severely limited realistic analyses. The procedures being developed by the National Environmental Satellite Center to derive high level winds from the satellite photographs were used, experimentally at first, to provide data for these analyses. The procedure, now operational, was started in March 1967. Estimates of the wind directions and speeds at both the 300 and 200 mb levels are made for as many as 200 positions every 24 hours. These estimates are plotted in the form of wind vectors on charts transmitted twice daily via Weather Bureau facsimile lines to forecast centers in the United States. The data also are relayed via radio teletype to countries in the southwest Pacific. Each chart covers the 180 degrees of longitude viewed by the satellite during the preceeding 12 hours. The wind estimates are derived from the appearance and shape of cirriform clouds. The size, shape, and orientation of plumes from active cumulonimbus, cumulonimbogenitus, cirrus spissatus, and cirriform cloud shields are used in arriving at these estimates.

An objective technique was developed to compare these wind estimates with observed winds. Since satellite data are not usually coincident with synoptic observations, the comparisons were made by assuming persistence between the synoptic wind observations and the time of the satellite observations. The results show a close relationship between the estimated and the observed (measured) winds, particularly at the 200 and 300 millibar levels.

The use of satellite estimated winds in the data sparse tropical and subtropical regions has resulted in a definite improvement in the numerical analyses produced at the National Meteorological Center (Bedient, 1967). Comments received from the Tropical Analysis Center at Miami and from other weather centrals indicate similar improvement. These results emphasize the utility of satellite derived winds for describing the wind field. While climatological winds and persistence can still be used for analysis in the areas under discussion, the small number of datum points available result in a rather sketchy analysis. The satellite derived winds not only "fill in" in areas of sparse data, but also indicate the existence of wind anomalies which could not be detected by reference to persistence or climatology.

II. CLOUD FORMATIONS FROM WHICH WIND ESTIMATES CAN BE MADE

The location of cyclones, anticyclones, troughs, ridges, and wind maxima in the upper troposphere can often be determined by visual inspection of cirrus formations appearing in satellite cloud photographs (Johnson, 1966). The scale of phenomena may range from the plume produced by a isolated cluster of cumulonimbi to the high level outflow over a hurricane to the cirrus patterns of a complex jet stream. Thunderstorm occurrence is a daily event over large areas of the tropics and subtropics. Cirrus also is commonly found with almost all frontal systems, jet streams, tropical and extratropical vortices, and vorticity maxima.

The idea that estimates of the high level wind flow could be derived from the appearance of clouds is not new. Wind directions obtained by reference to cirrus anvils stretched out from tops of cumulonimbus clouds and to jet stream cirrus have been reported in several previous papers (Johnson (1966), Kadlec (1963), Oliver, et al (1964), and Viezee, et al (1966)).

This paper describes the first attempt to use a systematic procedure to obtain wind estimates routinely on a global scale for use in current analysis and prediction.

Using Cumulonimbus Plumes

Cirrus blow-offs from cumulonimbus can be recognized by the hard, sharp edges on the upwind side and the filmy, wispy appearance on the downwind side of the cloud mass. An example of well developed plumes indicating ENE winds is seen in figure 1. Figure 2, a Gemini photograph, shows long plumes in silhouette along the horizon at sunset. Note their length in relation to the width of the convective towers. Wind estimates are obtained from the orientation and dimensions of cirrus blowing off from the tops of cumulonimbus. Where the flow at cirrus levels is moderately strong, twenty knots or better, the orientation of the plume is quite representative of the wind direction. In the case of light winds, those less than 20 knots, direction estimates must be made cautiously. Since light winds are less persistent in direction than strong winds, an estimate of a light wind becomes less accurate as the time difference between the satellite observation and synoptic time increases. Differential shear effects must also be considered. If the direction of the shear through the convective layer is considerably different than the direction of the wind at the top of the layer, the orientation of the plume can be misleading. This condition is common in frontal areas, where temperature advection usually is strong, but occurs less frequently in the tropics. In the tropics and subtropics, wind estimates made from cloud data have closely approximated the winds observed from 200 to 300 millibars.

Using Jet-Associated Clouds

Many investigators, Kadlec (1963), Oliver, et al (1964), Whitney, et al (1966), have shown that cirrus clouds frequently occur along and on the tropical side of jet axes, either as broad shields or as long narrow bands of cirrus. An impressive amount of evidence indicates that such jet-associated cirriform clouds can be identified in satellite photographs with relative ease. These cloud formations identify the location and direction of motion of jet stream wind maxima. Figure 3 shows the cirrus shield associated with a jet stream extending from Mexico and southern Texas to just south of New York and thence over the Atlantic Ocean. The shadow cast by the cirrus on the lower clouds is best seen over the Central United States extending from southern Texas (29°N, 100°W) northeastward through Missouri to the East Coast of North America (37°N, 76°W) and eastward over the Atlantic near 38°N, 70°W. Cirrus associated with a subtropical wind maximum may be seen extending from Florida (26°N, 81°W) to 30°N, 65°W. Note the small-scale banded structure in this cirrus, perpendicular to the orientation of the large-scale band. Such bands, oriented perpendicular to the wind flow, are frequently observed in cirriform cloud.

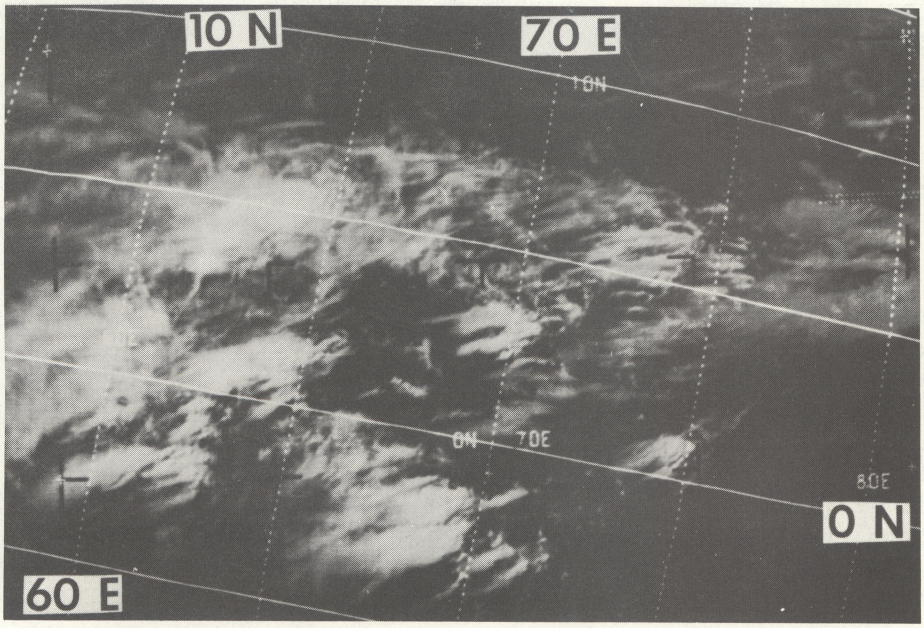

Figure 1. Well developed cirrus plumes over the Indian Ocean.

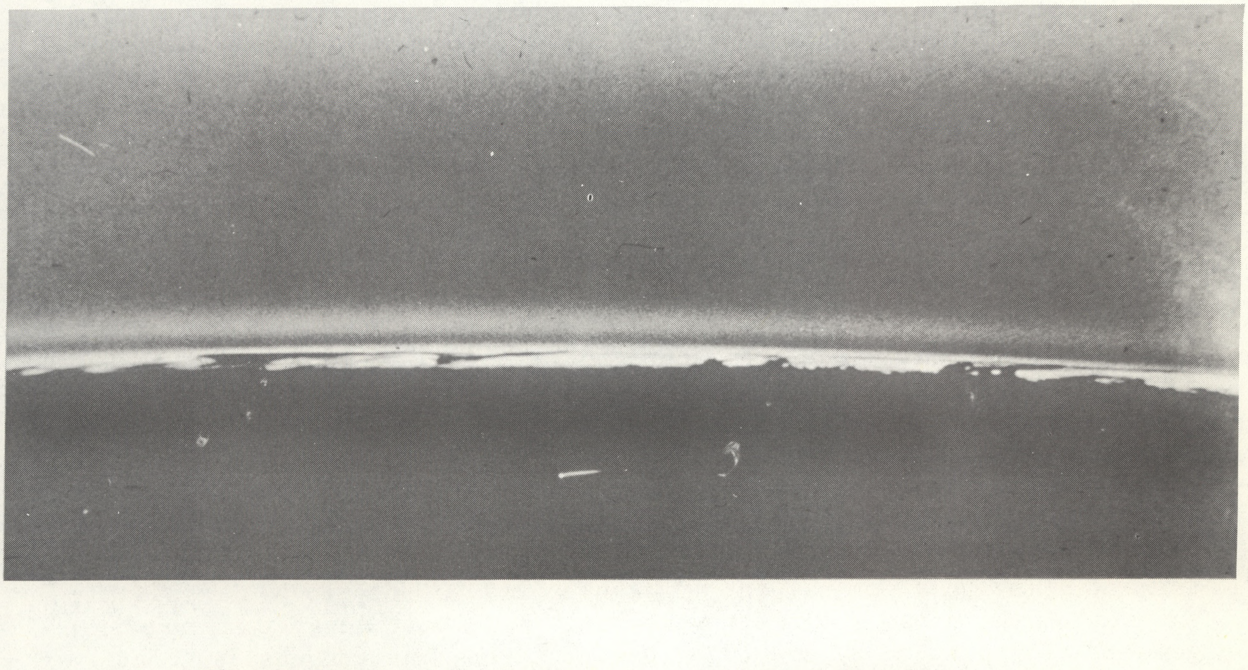

Figure 2. Gemini photograph. Long cumulonimbus anvils silhouetted at twilight.

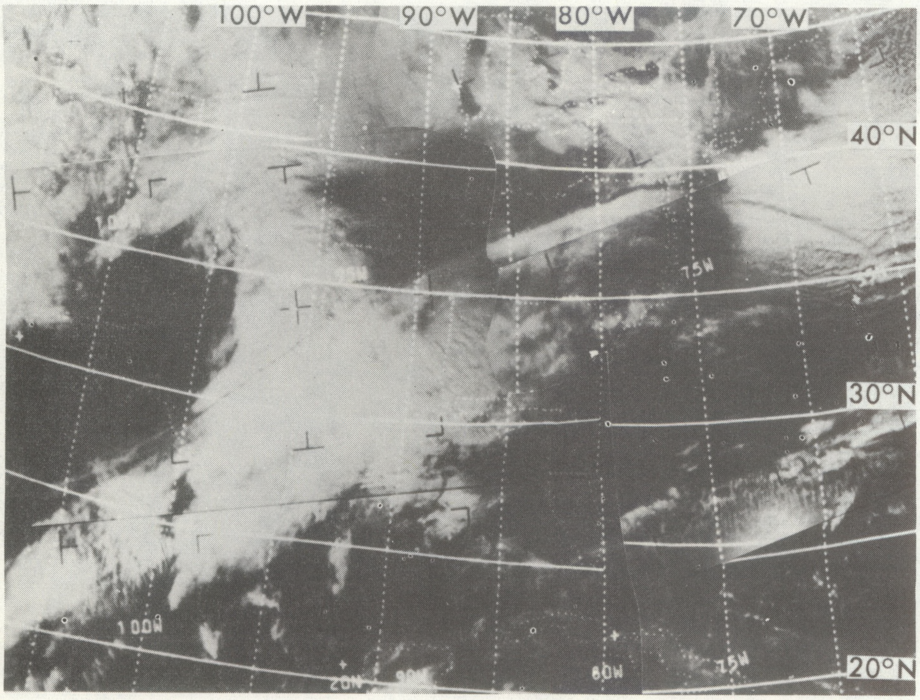

Figure 3. Cloud shadow indicating jet stream position, ESSA 3, 30 December 1966.

This transverse banding, which also includes transverse patterns of cirrus spissatus, occurs frequently, and should not be confused with cumulonimbus plumes oriented parallel to the wind. The typical appearance of cirrus spissatus over desert regions is shown in figure 4 (n.b., the area near 20°N and 5°W).

Estimates of the wind direction in the vicinity of cirrus clouds can be obtained from the pictures by the relatively simple, straightforward process of identifying the cirriform cloud formations and noting their orientation. Deducing the corresponding wind speeds is complex and subjective. The rules and techniques that follow are, in effect, a method for deriving a set of estimates of wind speeds and directions for one or more levels from the cloud patterns observed in satellite photographs.

III. OPERATIONAL PROCEDURES

The first step in using satellite cloud pictures as a means for estimating the winds is to examine the data over a relatively large area. One should first familiarize himself with the large-scale flow patterns indicated by the arrangement of the clouds. Trough and ridge positions are reliable indices to the broad scale flow pattern. After one has determined the general flow pattern by examining the pictures, one can easily locate smaller scale currents in the main flow, and weaker branching currents.

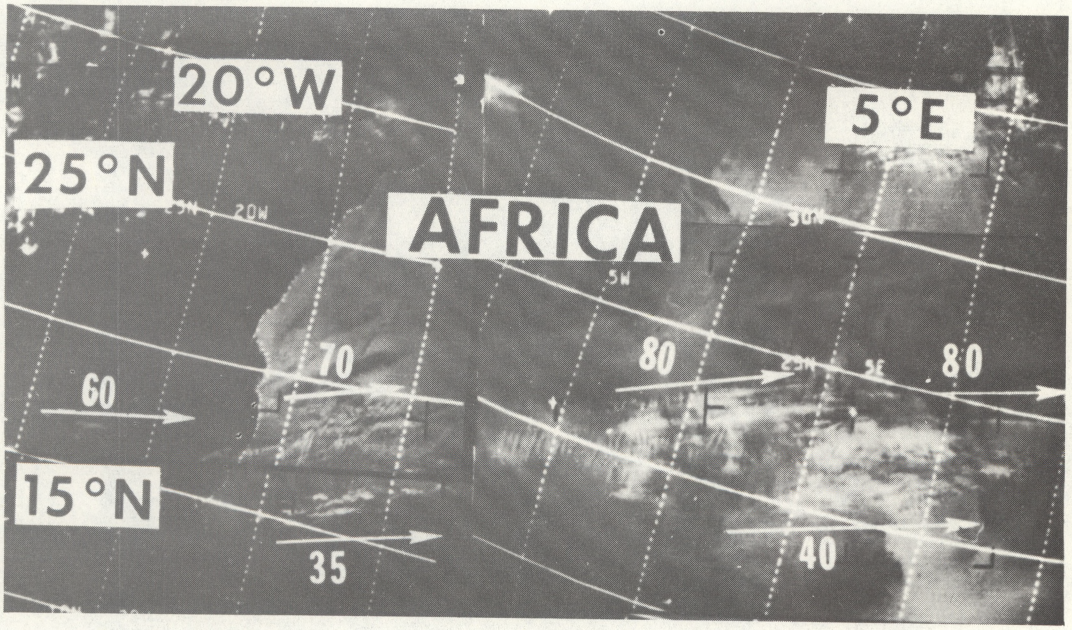

Figure 4. Cirrus spissatus over Sahara Desert, ESSA 3, 29 December 1966.

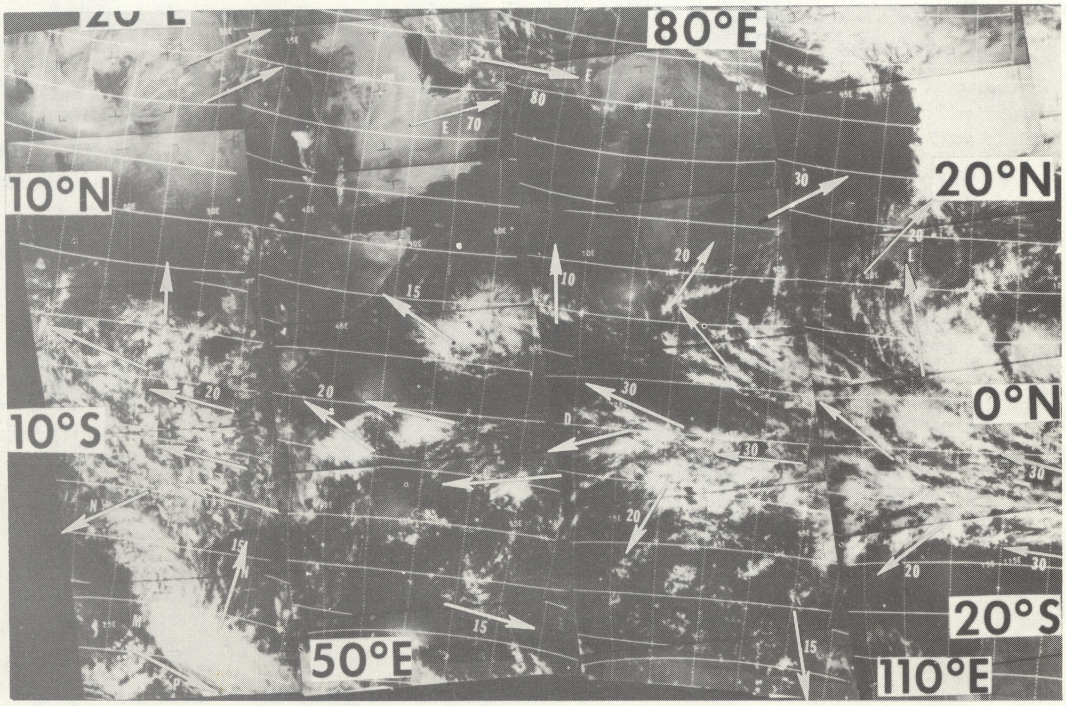

Figure 5. Estimated 200 mb winds over the Indian Ocean as derived from the clouds, ESSA 3, 25 February 1967. Arrows show estimated directions. Estimated speeds are indicated by each arrowhead.

The orientation and appearance of cirriform cloud are the primary features used in making these determinations. An example of how clouds reflect broad scale upper level currents is shown in figure 5. The broad scale easterly flow is nearly continuous from south of Sumatra to Eastern Africa. Branching flow is seen to the north and south. The cloud formations over Eastern Arabia and Pakistan are jet stream cirrus with transverse waves. In the lower left cirrus outflow above a low level cyclonic circulation may be seen.

The second step in analysis is to estimate the wind speed in areas where cirriform cloudiness is observed. It has been found by experience that speed estimates, based on the appearance of the clouds, should be restricted to three major categories: strong winds with speeds greater than 50 knots; moderate winds with speeds of 20 to 50 knots; and weak winds with speeds less than 20 knots. At the request of the National Meteorological Center, the wind speed estimates are made for five knot increments in the light and moderate categories and ten knot increments in the strong category. As will be shown later, this did not introduce any serious errors but, in fact, indicated the practicability of using such increments especially in the moderate and strong categories. The incremental wind speed estimates provided are compatible with conventional and numerical analyses.

The following rules developed for making these wind speed estimates include using the appearance of the clouds at the time of the picture, climatology, and continuity.

Rules

1. If a cirriform cloud formation suggests the proximity of a jet axis, the winds are considered strong.

2. The presence of transverse bands in cirrus indicates strong winds.

3. In a very general sense, the longer the plumes, the stronger the winds.

4. Outflow areas, indicated by the presence of diverging filaments of cirriform cloud, are generally indicative of light winds. In well developed tropical storms, however, the winds can exceed 30 knots on the periphery of the storm with this type of cloud pattern. Fujita, et al (1967) proposed a model of the 200 mb flow around a mature typhoon. The diagram (figure 6) shows the relationship of the strong peripheral winds at the cirrus level to the storm as a whole.

5. Large-scale currents extending in one direction for hundreds of miles indicate moderate winds. In the tropics these currents are characterized by well defined, often rather long plumes, oriented in the same or nearly the same direction. An excellent example of such a pattern over the Indian Ocean east of Somalia is seen in figure 7.

6. Areas exhibiting a change in orientation of the plumes within short distances indicate the presence of weak winds.

7. Westerly flow originating in equatorial areas generally becomes progressively stronger with increasing latitude.

8. Climatological wind roses, and mean wind direction and wind speed charts are particularly helpful in keeping estimates of wind speeds within reasonable limits for a given area. Figure 8 is an example of a wind velocity chart derived from climatological data for use as a guide in making wind speed estimates.

9. Check nearby wind reports from previous and recent upper air charts to assure against making unreasonable wind estimates.

10. Tropical regimes are quite conservative in contrast to middle latitude systems. All NAVAER Vector Standard Deviation charts (U. S. Navy, 1958) show a minimum near the equator, and steady increases with increasing latitude. This rule should be used with Rule 9. These two rules provide continuity and persistence checks respectively.

11. Cloud formations in close proximity, and oriented so that wind directions appear diametrically opposed to one another (or nearly so), are indicative of very weak winds except in a few areas of the subtropics. One area where such an exception applies is over southern Arabia in autumn. Here winds shift rapidly from easterly to westerly with increasing latitude, and with very little change in strength.

12. Over tropical storms, where high level outflow is evident in the clouds, the wind estimates pertain to upper flow (200 mb) and cannot be extrapolated to lower levels. The flow at the 250 and 300 mb levels often is cyclonic rather than anticyclonic as at 200 millibars.

13. In dealing with wind maxima such as those associated with jet streams, it is often desirable to make corrections for the change of speed with height. The use of a climatological atlas such as the NAVAER Marine Climatic Atlas to determine a normalized wind profile gives the best results.

14. Empirical rules for various local areas are helpful. For example, Indian meteorologists associate strong high level easterlies over the Bay of Bengal with greater than usual convective activity and weaker winds with diminished convection.

15. If in doubt about a wind direction, do not make an estimate.

In several of the above rules the use of climatological data is mentioned. Charts of the type shown in figures 6 and 8 are very useful as controls on estimates. The plume lengths can be quickly checked to ensure a reasonable wind speed field. Charts of the type shown in figure 8 are also very useful in training personnel who must work on a global scale. It shows local peculiarities, such as rapid changes in wind directions or speeds, which may be unfamiliar to an analyst in a center many thousands of miles away. The same reasoning applies to the variation of wind speed with altitude. There is no present method for determining from the photographs variations in speed between the 200 and 300 millibar levels. The use of a seasonal normal wind profile, especially one based on a representative period of observation, will permit reasonable estimates which are sufficiently accurate for most uses.

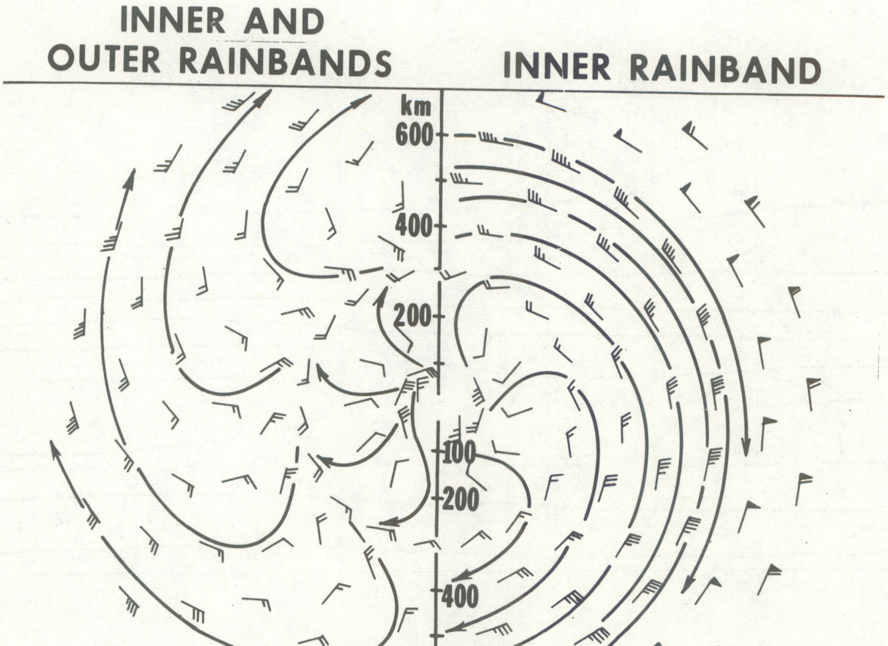

Figure 6. Model 200 millibar flow around mature typhoon.

Figure 7. Long parallel plumes over Indian Ocean.

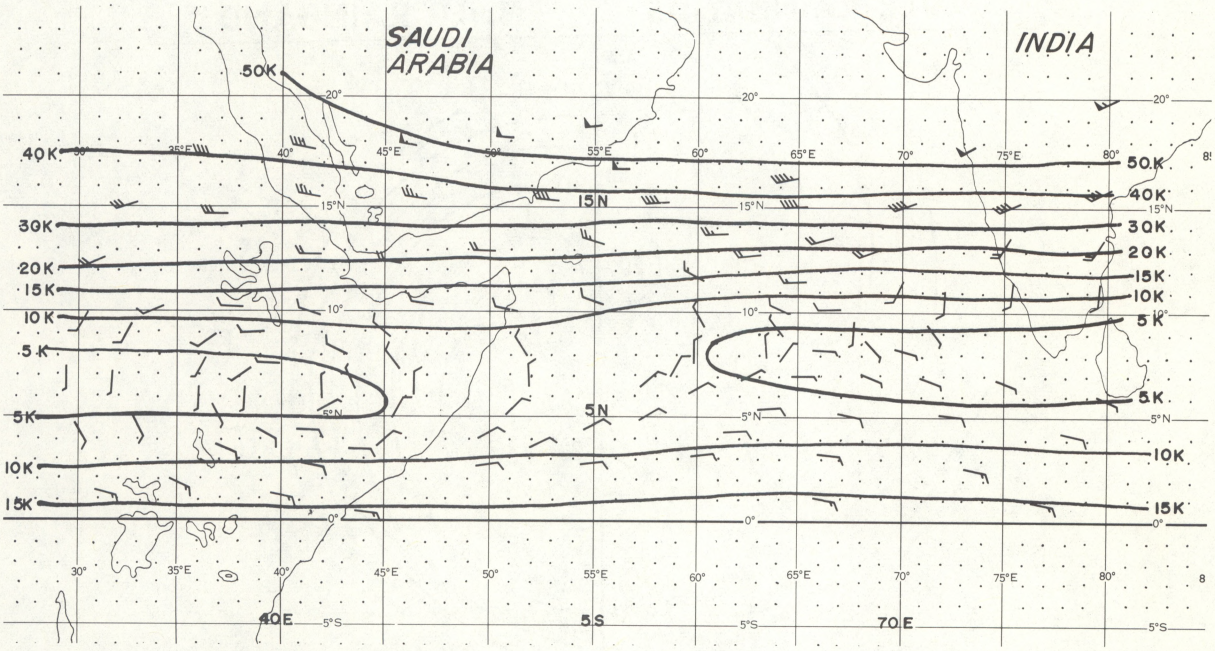

Figure 8. Vector mean wind speeds and directions,
200 mb, December, January and February.

IV. CURRENT USE OF DATA

The first step of the procedure, currently in use at the Analysis Section of the National Environmental Satellite Center, is the analysis of the pictures using the fifteen rules listed above. The derived wind estimates are then plotted on a 1:20,000,000 mercator chart (figure 9). The deadlines for completing this chart are 0215 GMT for the area from 30°E to 150°W, and 1415 GMT for the part covering 150°W to 30°E. The estimates are then encoded as wind reports and are passed to the Computation Division of the National Meteorological Center to be used in the numerical tropical analyses. These estimates are transmitted in chart form via facsimile and in encoded form by teletypewriter twice daily. The encoded winds also are transmitted in digital form to several other weather centrals for use in their analyses. An example of a 200 mb analysis which incorporates both reported winds and winds estimated from the cloud photographs is shown in figure 10. The plotted reports on this figure are those derived from the satellite data. One program in use at the Navy Fleet Weather Central, Monterey, California, converts the wind estimates into specific values for a grid point array. These values are then used as data in the upper air analysis and forecasting program. At the Regional Center for Tropical Meteorology at Miami, the plotted wind estimates received by facsimile are replotted on the 200 mb chart and are used as observed data. Figure 11 shows the Miami Center 200 mb analysis for 0000Z 17 October 1967 with the satellite derived winds used in its production. These illustrations show that the wind estimates from satellite pictures are a major source of data for upper level wind analysis in the tropics. Except for some continental regions and a few oceanic areas with a high density of AIREPS, these latitudes may be considered data sparse at upper tropospheric levels around the entire world.

Lack of data is especially critical to current numerical analysis procedure and forecast model used by the National Meteorological Center for the tropical regions. When the wind field is not completely specified along the length of a strong zonal current, the numerical analysis procedure almost always introduces fictitious meridional components into the wind field. This error is retained and magnified during successive time steps in the forecast routine. In areas where no conventional wind reports are available, the forecast wind field becomes the "first guess" for the next computer analysis. Thus, errors introduced because of lack of data tend to propagate and increase in magnitude with time. The addition of even a few wind estimates along a zonal current results in a far better initial analysis. Figure 12A shows the 200 mb analysis, based on observed winds only, for 0000 GMT March 6, 1967. This analysis represents the "first guess" wind field available for the 1200 GMT computer analysis. Note the northeasterly flow across the equator between 35°E and 70°E and the single anticyclone over the Indian Ocean. Figure 12B shows the 1200 GMT analysis

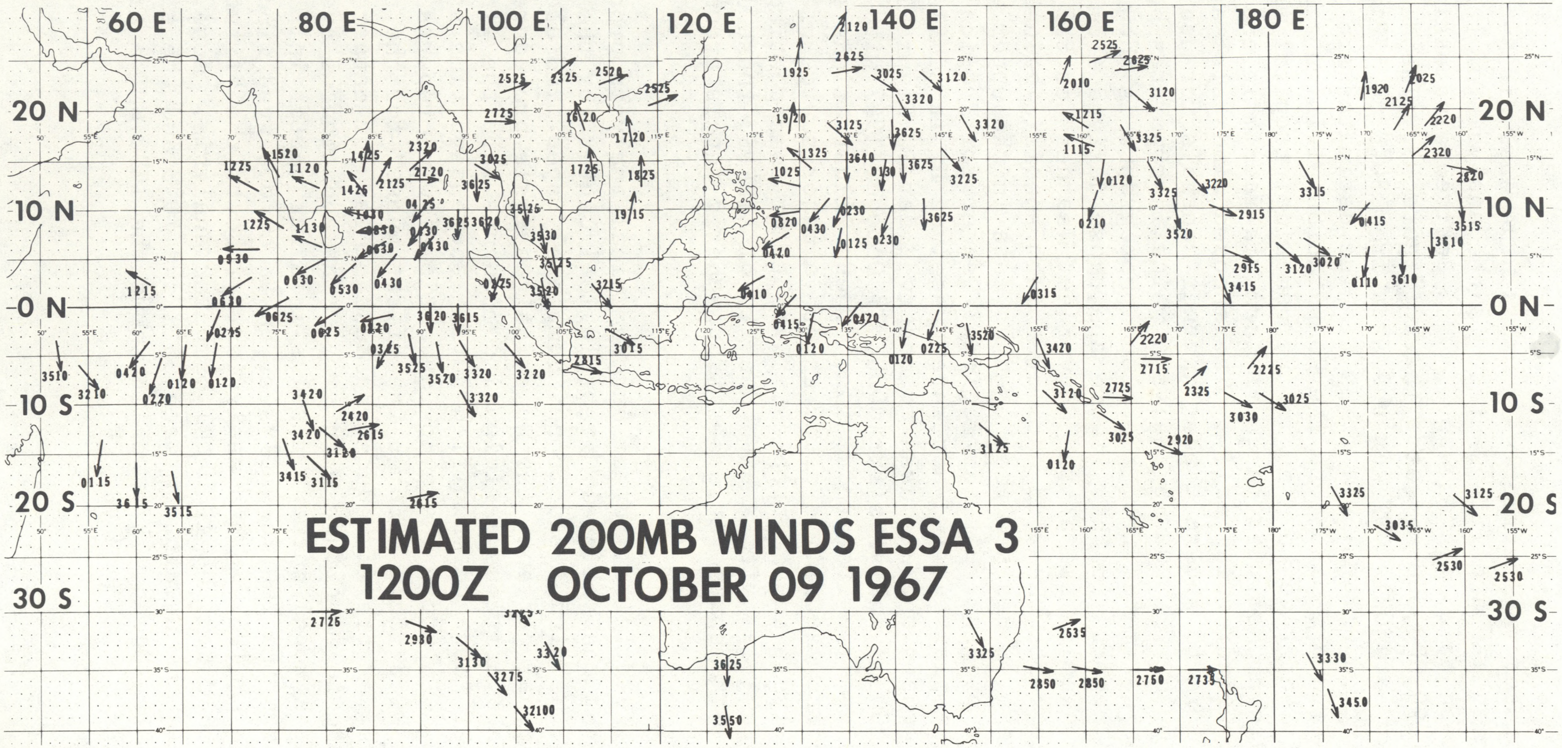

Figure 9. Estimated 200 mb winds derived from ESSA 3 data for a 24-hour period.

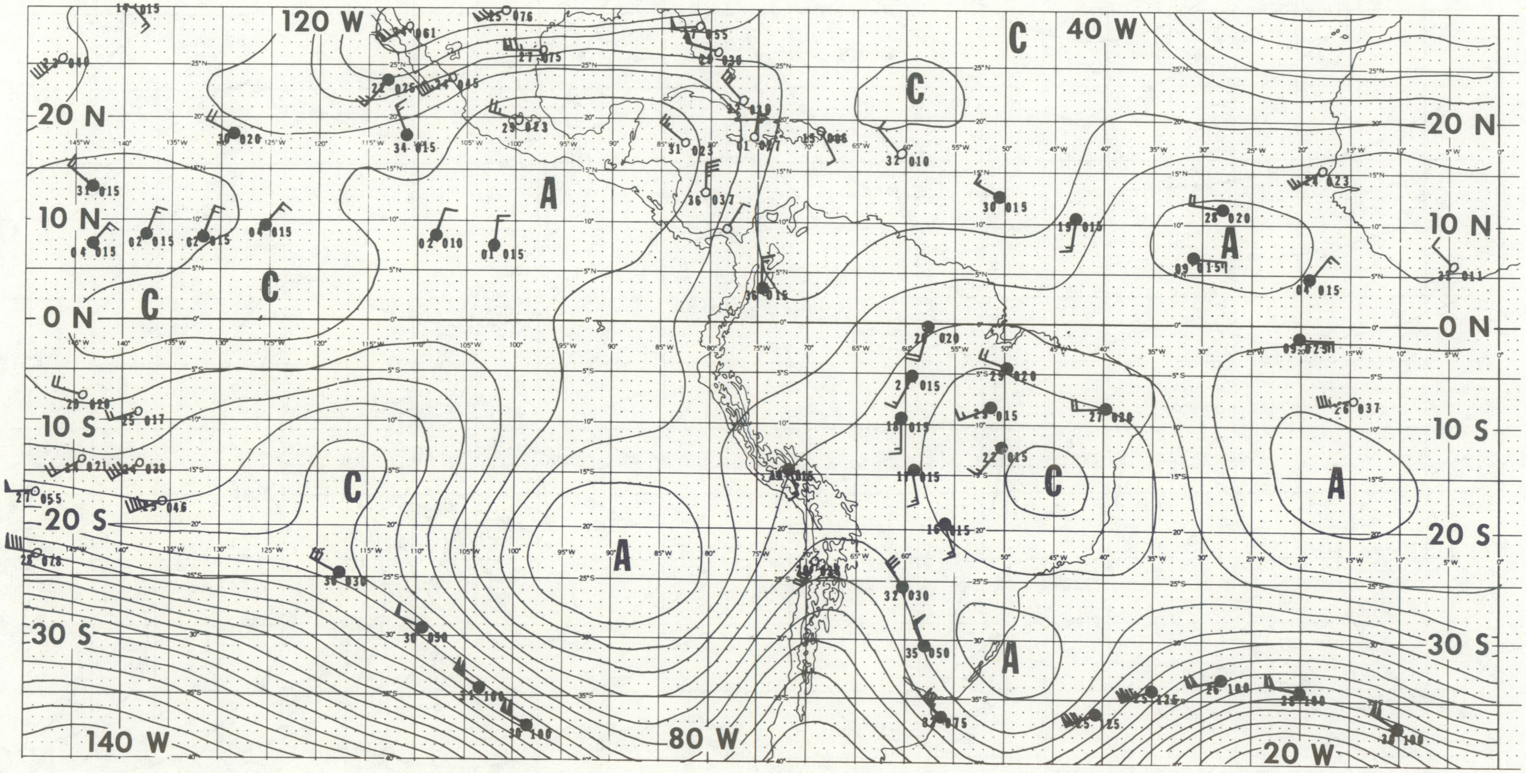

Figure 10. Estimated 200 mb winds and NMC 200 mb analysis for 0000 GMT, 12 October 1967.

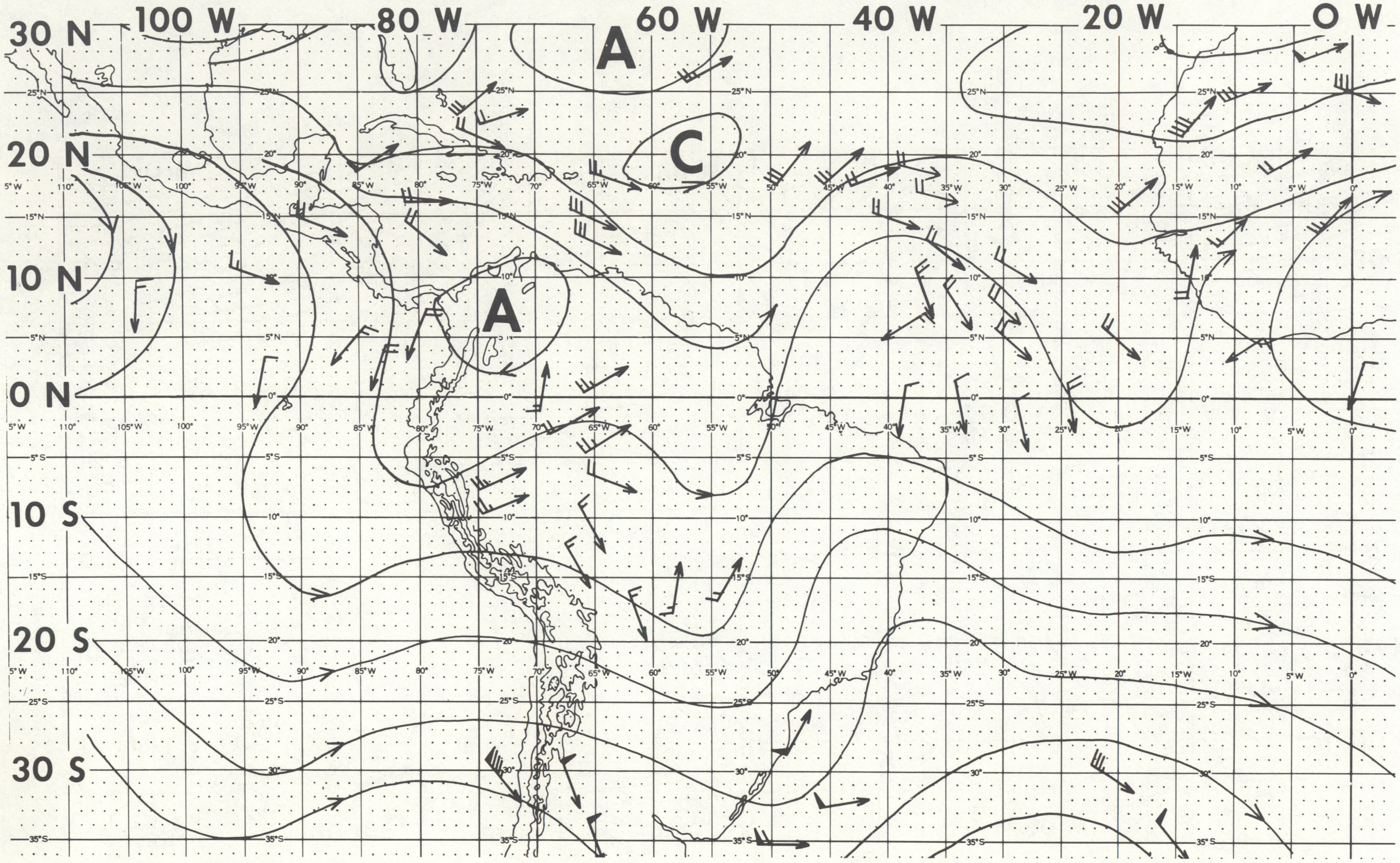

Figure 11. Estimated 200 mb winds and Miami analysis for 0000 GMT, 17 October 1967.

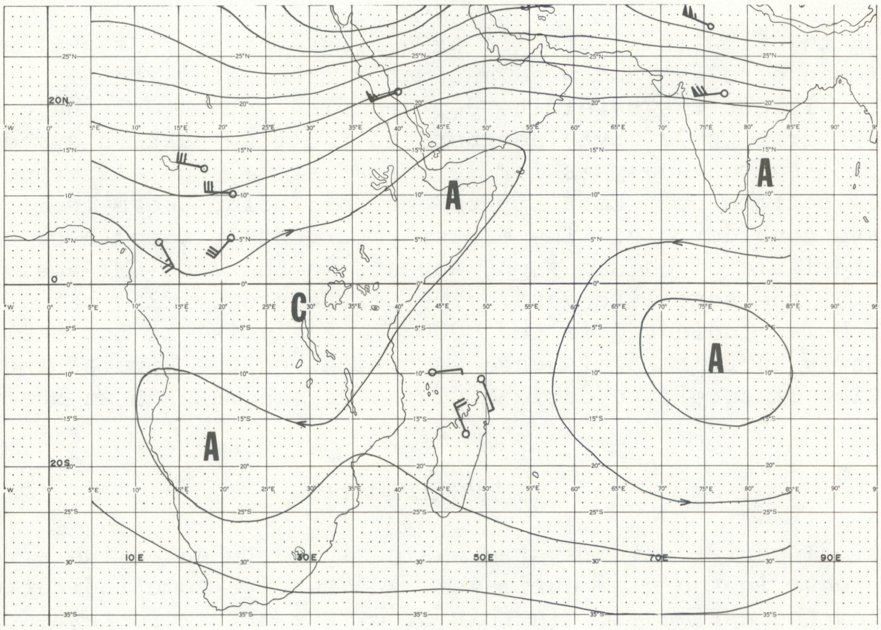

Figure 12A. First guess field for the NMC 200 mb numerical analysis for 1200 GMT, 06 March 1967.

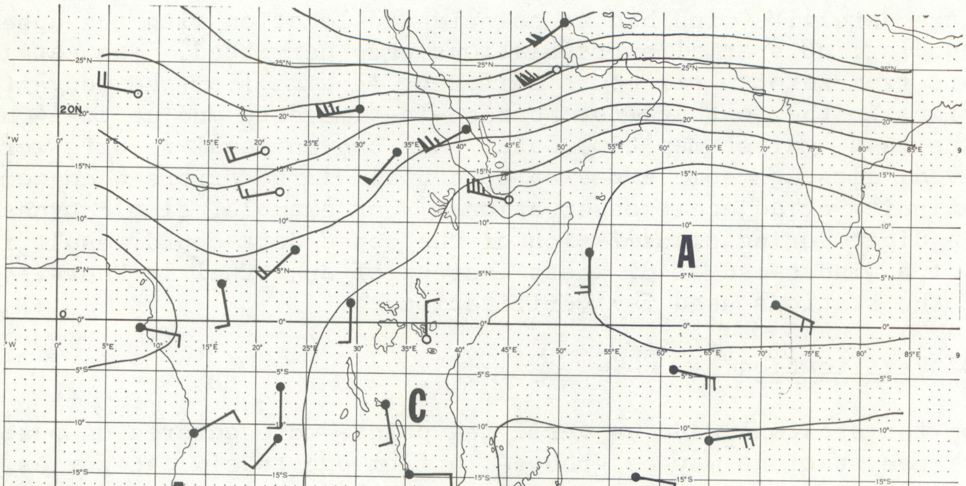

Figure 12B. Final 200 mb numerical analysis for 1200 GMT, 06 March 1967. Arrows with solid circles are satellite estimates.

made using the flow in figure 12A as a first guess, plus available wind reports (open circles) and wind estimates from satellite pictures (solid circles). Without the satellite derived wind estimates, the computer analysis program would have incorporated the flow pattern appearing in figure 12A into the analysis for 12 hours later. The differences in the basic flow pattern over East Africa and the Indian Ocean in figures 12A and 12B are considerable. The easterly current just south of the equator, so characteristic of this season, appears in the 1200 GMT analysis which incorporates the satellite data. The northeasterly flow between 35°E and 70°E, which was indicated in the 0000 GMT analysis, is now shown to be a southwesterly current. This case is typical of the kind of improvement the addition of satellite derived wind data can make in an analysis.

V. VERIFICATION

A statistical verification system was designed to determine errors, and error sources, in the wind estimates, and to give some indication of the accuracy of the estimates. In this study the data were tested in two modes. In the first, satellite derived wind estimates were compared with observed winds closest in time to the satellite observation. The maximum difference between the time of the estimated wind and that of the observed wind is ± six hours. In the second test, the estimates were compared to wind reports received at the time of the analyses in which they were used. Checks were also made against persistence. In all cases used for verification, the satellite wind had to coincide in location with the upper level sounding; no spatial extrapolations were permitted. The satellite winds were from zero to six hours different in time from the conventional observations in the test against nearest-in-time data and up to 14 hours old in the test against map time data. All conventional reports were used as received, although some appeared to contain large errors when compared with continuity or adjacent observations. For example, simple transposition of a digit during transmission of the coded data could result in receipt of a wind speed of 81 knots instead of an actual 18 knots. Figure 13 shows the stations used for verification.

Method of Verification

Data from the stations used as verifying points were entered on punch cards. These stations may be grouped in from one to six categories. A station may be in one or all categories. Thus, statistics for the stations as a whole may be obtained by putting all stations in one of the categories. Each category may have up to 200 stations.

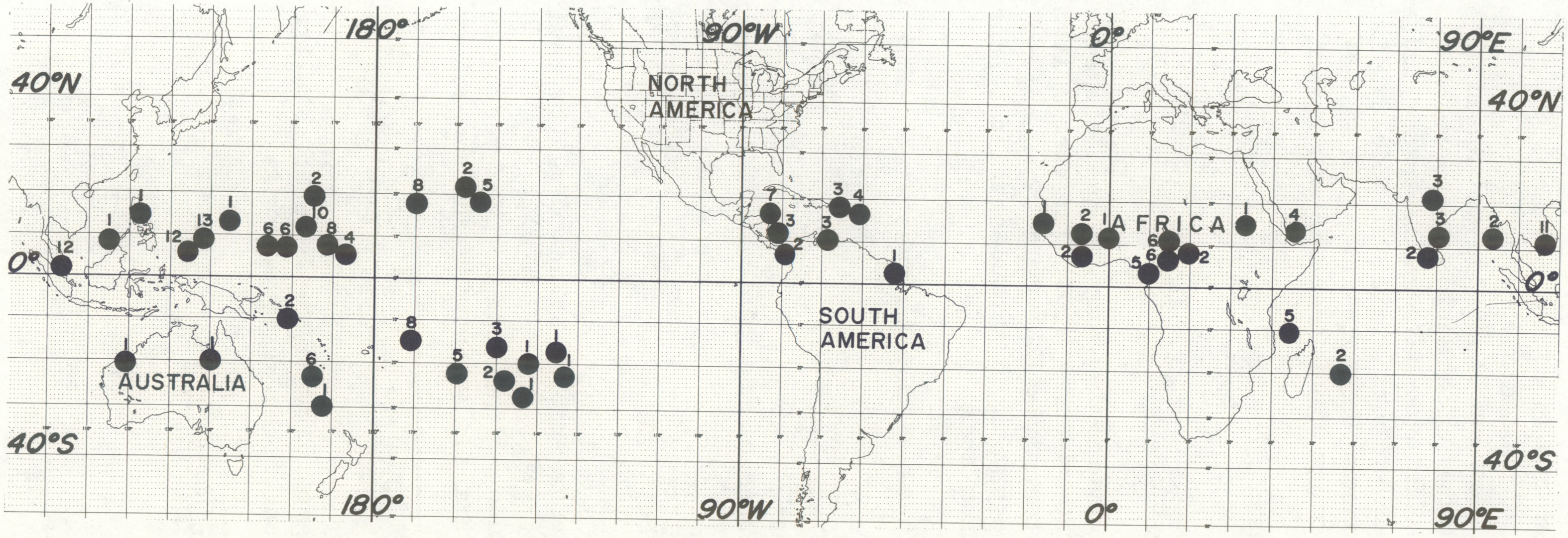

Figure 13. Stations used in verification program. The number of cases verified is indicated above each station circle.

The data are punched on cards and provide the following information:

1) Station Number
2) Level of the Wind
3) Satellite Wind Direction and Speed
4) Observed Wind Direction and Speed
5) Time Difference between Observed Wind and Persistence Wind
   (= 0 if no persistence wind is available in 24 hours.)
6) Persistence Wind Direction and Speed
7) Climatology Wind Direction and Speed.

One card is used for each satellite wind.

Statistics Calculated:

As an aid to determining differences, the statistics are separated by the quadrant of the observed wind: Quadrant 1 is 0° to 80°; Quadrant 2 is 90° to 170°; Quadrant 3 is 180° to 260°; Quadrant 4 is 270° to 350°. There is also a category which includes all quadrants. The statistics calculated for each station are:

1. Mean Speed of the Observed Wind:

$$\overline{S_o} = \frac{1}{n} \sum_{i=1}^{n} S_o$$

S_o observed wind speed

Mean Speed of the Wind as Estimated from Satellite Cloud Pictures:

$$\overline{S_s} = \frac{1}{n} \sum_{i=1}^{n} S_s$$

S_s Speed of wind as estimated from satellite picture

2. RMS Vector Error: Standard vector deviation

Magnitude of the mean of that vector which is the difference between the estimated wind and the observed wind.

$$\mathrm{RMS} = \sqrt{\frac{1}{n}\left[\sum^{n} (U_s - U_o)^2 + \sum^{n} (V_s - V_o)^2\right]}$$

in which the X, Y components of respective winds are used.

3. Difference between the mean of satellite estimated wind speed and the mean of the observed winds.

$$\overline{(S_s - S_o)} = \frac{1}{n} \sum^{n} (S_s - S_o)$$

algebraic

4.

$$|\overline{S_s - S_o}| = \frac{1}{n}\sum^{n} |S_s - S_o|$$ absolute

5. Difference between mean of estimated wind direction and observed wind direction.

$$(\overline{D_s - D_o}) = \frac{1}{n}\sum^{n} (D_s - D_o)$$ algebraic

6.

$$|\overline{D_s - D_o}| = \frac{1}{n}\sum^{n} |D_s - D_o|$$ absolute

Verification Results

The verification procedure was followed for five months, 1 May to 30 September 1967. During this period, 210 cases were obtained for 300 millibars and 197 for 200 millibars. In all of the cases verified, the satellite wind estimate coincided with the location of the upper wind sounding station. Due to the sun synchronous orbit of the satellite, a satellite observation will rarely be synoptic with an upper level sounding.

Table 1 shows some of the verification results for 200 mb winds. The data were treated in two categories: one containing all observed winds with speeds equal to or less than 20 knots (weak winds), the other in which the observed speeds were greater than 20 knots (strong winds). Comparisons were made between satellite estimated and observed winds, and between persistence and observed winds. As shown in the table, the RMS vector differences in wind speed obtained by using satellite estimated winds were little different from those obtained by using persistence. This close correspondence engenders confidence in the use of satellite estimated winds over areas where no conventional data are available.

The statistical analyses for the 300 mb wind estimates were essentially equivalent to those for the 200 mb level. Verification against map time data, (satellite observations up to 12 hours old), showed slightly larger differences between satellite estimates and observations. Smaller differences were noted in the latter months of the test.

In general, over the region bounded by 30°N - 30°S, the estimated winds fit best with the reported winds at 200 mbs. Farther north or south, especially in the winter season, the fit is best at a lower level, usually near 300 millibars. Assuming that the observed cirrus is below the tropopause, one should expect the level of best fit slightly below the tropopause. Thus, seasonal charts of tropopause heights should be used to determine this level. In several cases, estimated winds which did not agree

Mean Windspeed (kts)	Observed at 200MB within ± 6 hrs	Estimate from Satellite Pictures	RMS Vector Difference S_s , S_o	RMS Vector Difference * S_p , S_o	$\overline{(S_s - S_o)}$	$\lvert\overline{S_s - S_o}\rvert$	$\overline{(S_p - S_o)}^*$	$\lvert\overline{S_p - S_o}\rvert$
≤ 20	15	13	24	21	-2	7	+3	10
> 20	42	28	25	25	-14	16	-5	14
Mean Wind direction (degrees) with speeds of					$\overline{(D_s - D_o)}$	$\lvert\overline{D_s - D_o}\rvert$	$\overline{(D_p - D_o)}^*$	$\lvert\overline{D_p - D_o}\rvert$
≤ 20 kts					-5	59	+17	55
> 20 kts					-6	22	-20	30

* S_p - Wind speed determined by persistence
D_p - Persistence wind direction

Table I. Verification results for 200MB winds, I May - 30 September 1967

Table 1. Verification results for 200MB winds, 1 May - 30 September 1967

with a nearby 200 mb observation did fit very well with the observation at a higher level. In all such cases, the tropopause was higher than usual and, as expected, above the level where the estimated winds fit the observation.

VI. FUTURE APPLICATIONS

The Applications Technology Satellite (ATS) suggests another approach for obtaining wind estimates. From its quasi-stationary position at 22,300 miles above the equator, the ATS spacecraft has the capability of photographing almost an entire hemisphere once every 15-30 minutes. Carefully rectified ATS pictures have been viewed by means of time-lapse films from which cloud motion measurements, rather than estimates, can and have been made. Investigations thus far show that such measurements are possible at more than one level over a given area. Time-lapse motion pictures have been produced by the University of Wisconsin, the University of Chicago, and the National Environmental Satellite Center. These films indicate that operational application of this technique now depends merely on developing the capability to produce films in time for operational usefulness.

VII. CONCLUSIONS

The upper tropospheric winds estimates derived from satellite photographs are considered a reasonable approximation of observed wind speeds and directions. The rules and techniques described are considered valid, and may be used with a relatively high degree of confidence. These rules are most easily used in the tropical and subtropical regions, and may be used in other regions during seasons of heavy cirrus production. The estimated winds prepared daily by NESC personnel are being used operationally by the National Meteorological Center, the Regional Center for Tropical Meteorology at Miami, various civilian and military weather centers in the United States and overseas, and by several foreign meteorological services. All have reported on the usefulness and importance of these estimated winds to their operations. The rapidity of widespread acceptance and use of this product testifies to its usefulness. Continued refinement of techniques will improve its accuracy.

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