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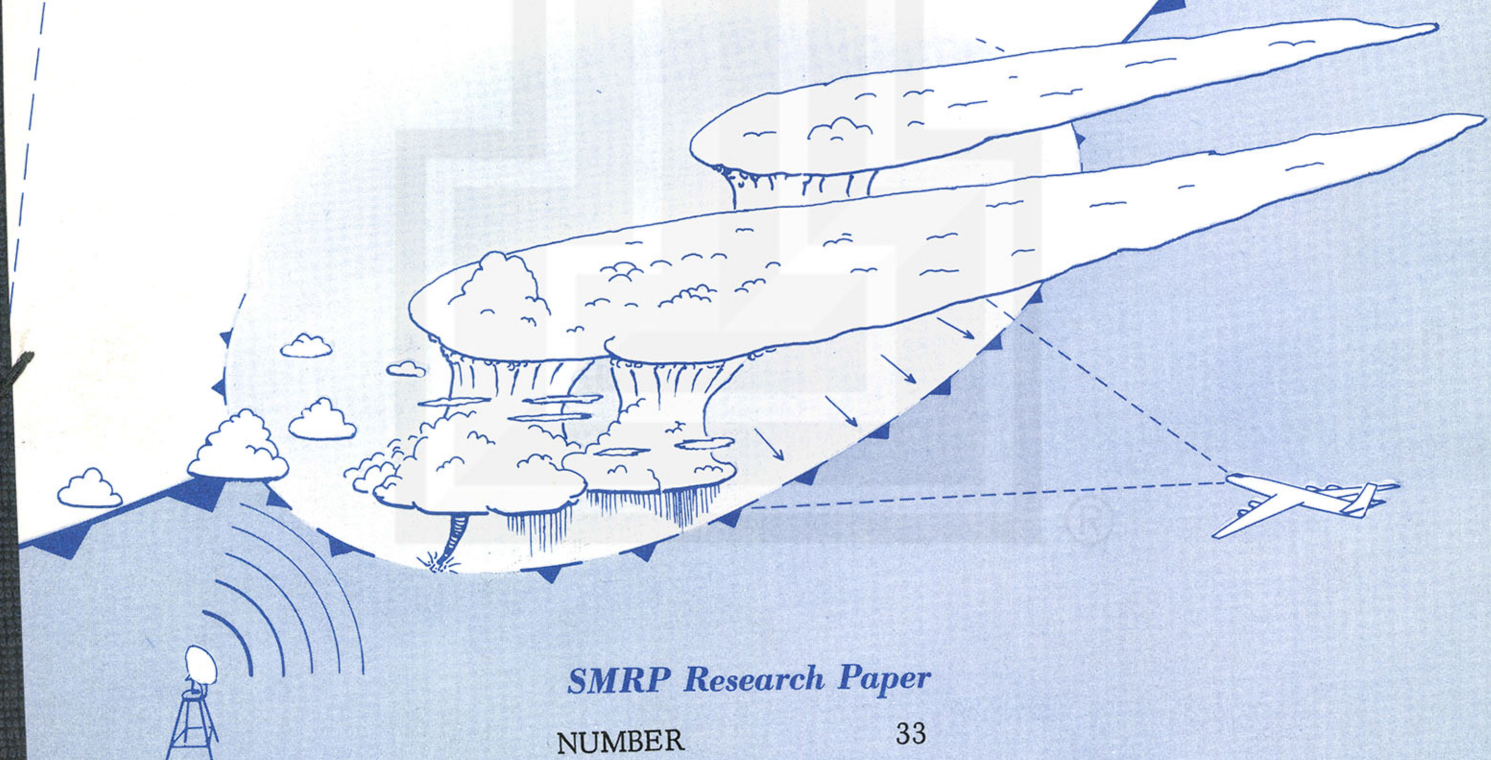
SATELLITE & MESOMETEOROLOGY RESEARCH PROJECT

Department of the Geophysical Sciences
The University of Chicago

A STUDY OF CUMULUS CLOUDS OVER THE FLAGSTAFF RESEARCH NETWORK WITH THE USE OF U-2 PHOTOGRAPHS

by

Dorothy L. Bradbury and Tetsuya Fujita



SMRP Research Paper

NUMBER 33

July 1964

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The research here reported has been sponsored by the Atmospheric Sciences Section, National Science Foundation under grant G-18984 and in part by the Air Force Cambridge Research Laboratories of the Office of Aerospace Research, USAF, Bedford, Mass., under Contract No. AF 19(604) - 7259.

A STUDY OF CUMULUS CLOUDS OVER THE FLAGSTAFF RESEARCH NETWORK WITH THE USE OF U-2 PHOTOGRAPHS

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ABSTRACT

Using cloud photographs taken by a U-2 aircraft equipped with a 180-deg panoramic camera, a technique of rectification is described. Mosaics of 13 passes over the San Francisco Mountains were made with the rectified cloud photographs. Computations of cloud movement and change in the horizontal area of cloud were made by use of cloud and cloud shadow. It was found that the computed cloud motions are within the range of the wind speeds reported from nearby upper air reporting stations.

1. Introduction

A number of investigations have been conducted to ascertain the nature and characteristics of convective clouds using aerial cloud photographs as a major source of data. Plank (1960, 1962, 1964) used photo reconnaissance observations during a nineteen-day period over the Florida peninsula to study the characteristics of cumulus cloud populations at the local and mesosynoptic scales. Wexler and Malkus (1958), Malkus, Ronne and Chaffie (1961) and Malkus, Riehl, Ronne and Grey (1961, 1962) have used aircraft cloud photographs to study cloud distributions and patterns over the tropical oceans and in the vicinity of a hurricane. Blackmer and Serebreny (1962) used U-2 cloud photographs in a study of dimensions and distributions of cumulus clouds. In these studies the sequence of cloud pictures over a specific area was limited and attempts to compute cloud motions and growth with only cloud pictures would have been difficult.

During the summer of 1960 a meteorological observation network was established in a thirty-by-forty-mile area around the San Francisco Mountains near Flagstaff, Arizona to gather data for research in mesometeorology and cloud physics. The equipment was installed and observations were taken by several cooperating agencies which included the Atmospheric Research Group, Air Force Cambridge Research Laboratories, the United States Weather Bureau, the University of Michigan and The University of Chicago. Figure 1 shows the network of stations and the various types of observations made.

The same network was in operation during the summer of 1961 and was supplemented on several days during July and August by a U-2 photographic aircraft based at Edwards Air Force Base, California. On 25 July the U-2 aircraft made a series of west-east and east-west passes over the San Francisco Mountains with Williams, Arizona or 112° 15'W as an approximate western limit and Sunrise Trading Post or 111° 00'W as the eastern boundary. Thirteen passes were made over the designated area during a period of approximately two hours and forty-five minutes centered around midday.

The cloud photographs were taken with a Perkin Elmer Model No. 501 panoramic camera with an angular coverage of 42 deg by 180 deg. The film is moved past a fixed slot in synchronism with a rotating prism to give a 180 deg presentation perpendicular to the direction of flight. A scan time of one-half second per picture is normally used. The interval between photographs was set for 32 seconds.

Only those pictures taken when the aircraft was flying in a straight path over the designated area were used. Thirteen overlapping frames, on the average, covered the west-east (east-west) distance. These cloud photographs form the basic data for this study. Since the aircraft flew over almost the same path on each pass the resulting cloud photographs provided almost ideal data for a study of cloud growth, cloud motions, and cloud distribution with respect to topography.

2. Photographic Rectification of Cloud Pictures

Because of the distortion inherent in the aircraft camera it was necessary to rectify each frame before matching up individual clouds to make a composite cloud picture covering each pass. This is a slow and laborious task if each frame must be manually rectified.[1] To speed up the process a photographic technique of rectification was devised by Fujita. The first step was to photograph the individual frames on 35 mm film from the 70 mm positive film displayed on the U-2 photograph analyzer. Figure 2 shows the analyzer which was designed and constructed at the Satellite and Mesometeorology Research Project and the camera holder devised for this operation. The next step in the procedure involved projecting the 35 mm negative in the enlarger upon the positive paper fitted over the surface of a curved easel as shown in Fig. 3. The radial and tangential distortions are represented by the two curves (R and T, respectively) shown in Fig. 4 and the curvature of the easel was a compromise between the two.

Figure 5 (a) shows a cloud picture taken with the aerial camera and 5 (b) is the same picture after rectification. The latter is as near distortion-free as could be obtained within the limitations of this system. Since only the central strip, approximately half of the area of the picture, was used in making the composite cloud pictures the matching of the clouds was quite accurate. The change in cloud form and size during a 32-second interval was minimized by this technique.

After the composite cloud photo was made for each of the thirteen passes a 15-minute latitude-longitude grid with smoothed mean topography was superimposed on the photograph. The grid served as an aid to observing the motion of clouds, the population increase of cloud with time, and the effect of topography on cloud growth.

The appendix contains the entire series of passes. Only a few have been used in the body of this report.

For a more detailed study of the motion and growth of individual clouds the apparatus shown in Fig. 6 was designed and constructed to support and carry the camera when photographing individual clouds from specific frames. A proper pitch angle grid was superimposed on the selected frame of 70 mm positive film displayed on the U-2 photo analyzer before the cloud was photographed. To rectify these

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[1]Techniques of photo rectification can be found in one of several textbooks on the subject of photogrammetry such as, American Society of Photogrammetry (1951), Moffitt (1959), and Hallert (1960).

individual cloud pictures a height grid of known scale was matched with the image pitch angle grid by tilting the base of the enlarger.

3. Change in Cloud Patterns with Time

The composite cloud pictures do not represent a simultaneous cloud pattern since a time interval of approximately 7 minutes elapses from the beginning to the end of one pass over the designated area. Because of this, and also the fact that almost the same amount of time is required for the aircraft to make the turn for the next pass, it is difficult to identify individual clouds from one composite picture to the next. Small clouds are very difficult to identify on two consecutive passes as they either expand and change shape or break up into smaller fragments and dissipate. Under certain conditions clouds of larger mass have more of a tendency to maintain their general features for periods up to 10 minutes or longer. This can best be illustrated by comparing individual clouds present near the end of one pass and those at the beginning of the next pass. Figure 7 shows the mosaic cloud pictures for passes 8 and 9. The elapsed time from the beginning of pass 8 to a corresponding point near the end of pass 9 is 17.6 minutes. No individual cloud could be identified in the right-hand portions of both passes 8 and 9. On the other hand, the time interval from a point near the end of pass 8 to the corresponding point near the beginning of pass 9 is 7 minutes. At the left-hand portion of these two mosaics individual clouds and groups of clouds can be identified and their motion and growth rate computed from such pictures. Figure 8 shows two more consecutive passes, numbers 11 and 12, about 34 minutes later. It is seen that the changes in cloud patterns at the eastern (right side) end of the cloud pictures are not as great as those at the western end.

The number of clouds in various size categories for each of the four 15-minute latitude-longitude areas bounded by $35^{\circ}15'$N, $35^{\circ}30'$N, $111^{\circ}15'$W and $112^{\circ}15'$W (Fig. 9) were counted for the thirteen passes. The results were summarized in Table 1. The outstanding features of this summary are:

a. The large increase and decrease in the number of clouds of the smallest area category (< 0.5 n mi^2) between two

Pass No.	Area (n mi²) →	A					B					C					D					Total No. of Clouds	No. with area > 5.0 n mi²
		≤0.5	>0.5 ≤1.0	>1.0 ≤5.0	>5.0 ≤10.0	>10.0	≤0.5	>0.5 ≤1.0	>1.0 ≤5.0	>5.0 ≤10.0	>10.0	≤0.5	>0.5 ≤1.0	>1.0 ≤5.0	>5.0 ≤10.0	>10.0	≤0.5	>0.5 ≤1.0	>1.0 ≤5.0	>5.0 ≤10.0	>10.0		
				10:57					10:59					11:01					11:03				
1		30	6	0	0	0	68	28	15	0	0	70	33	17	0	0	33	5	1	0	0	306	0
				11:18.6					11:16.6					11:14.8					11:13				
2		45	11	4	0	0	84	38	16	0	0	79	33	18	0	0	51	13	0	0	0	392	0
				11:27					11:29					11:31					11:33				
3		91	26	2	0	0	136	32	11	0	0	66	23	11	3	0	36	12	2	0	0	451	3
				11:47					11:45					11:43					11:41				
4		50	20	5	0	0	54	28	11	2	1	43	18	7	6	3	33	7	7	1	0	296	13
				11:57					11:59					12:01					12:03				
5		65	27	19	0	0	37	17	17	2	1	30	13	8	7	2	22	10	5	0	0	282	12
				12:16					12:14					12:12					12:10				
6		38	19	4	4	0	16	10	11	0	4	18	10	11	3	2	20	10	8	0	0	188	13
				12:21.5					12:23.5					12:25.5					12:27.5				
7		28	12	4	3	1	38	12	9	3	2	27	20	8	3	3	31	21	8	1	0	234	16
				12:39					12:37					12:35					12:33				
8		27	10	8	2	1	28	18	11	2	4	12	9	12	5	5	28	17	7	1	0	204	17
				12:45					12:47					12:49					12:51				
9		18	15	6	2	1	22	15	9	2	3	7	6	9	4	4	21	12	10	2	0	168	18
				13:01.5					12:59.5					12:57.5					12:56				
10		53	23	10	0	2	13	11	6	5	4	12	8	4	3	5	33	17	8	1	0	218	20
				13:06.5					13:08.5					13:10.5					13:12.5				
11		20	19	10	2	2	8	8	13	3	4	4	3	3	1	6	29	12	14	4	0	155	22
				13:24.5					13:23					13:21.5					13:19.5				
12		33	6	7	2	3	10	6	10	4	4	5	3	7	3	5	24	8	11	4	1	156	26
				13:31.5					13:33.5					13:35.5					13:37.5				
13		25	12	8	5	2	14	4	9	4	6	11	2	9	0	7	18	16	9	2	4	167	30

Table 1. Number of clouds in the various size categories in 15-minute latitude-longitude areas A, B, C, and D. Time (underlined) represents mean local time for picture over that area during Pass 2.

consecutive passes, especially in areas A and D. These two areas represent the least orographic effect. This variation in number of clouds of small size indicates that small clouds will dissipate rapidly and new ones form within a short interval of time.

b. The large number of clouds of smallest area category in areas B and C during the first three passes which then decreased with time while the number of clouds in the large area categories (> 5.0 n mi^2) increased with time. The orographic effect is greatest in sectors B and C and some of the clouds of small area tend to grow in size rather than dissipate.

c. There was a steady increase in the total number of clouds in the large area categories (> 5.0 n mi^2) beginning with pass 4. This may be attributed mainly to the increase in convective activity over the period. Net advection probably contributed a small amount to the increase but the major factor was the growth of small clouds into larger ones in the regions of increased upward motion.

4. Cloud Area Computations

An attempt was made to compute the change in horizontal area of cloud mass between two consecutive passes. It was found that the cloud mass straddling latitude circle $35^{\circ}15'$N midway between longitudes $111^{\circ}15'$ and $111^{\circ}30'$W on pass 11 increased in area by approximately 18% during the 5.5 minute interval between passes 11 and 12. At this rate of increase the cloud area would double its size in thirty minutes. This is not an unrealistic approximation as is shown in Fig. 10, a graphical representation of the total cloud area in sectors A, B, C, and D for the thirteen passes. Between pass 1 and pass 3 (approximately 30 minutes) the total cloud area nearly doubled; between passes 1 and 4 (44 minutes) it more than doubled; and by pass 10 (almost a two-hour interval) it had tripled.

The smaller rate of increase in total cloud area after pass 3 may indicate that the rate of growth of small clouds is greater than that of large size clouds. The number in the small size category decreased after pass 3 while those in the large size category increased.

5. Computation of Cloud Motion

Computations of cloud movements were made from the two passes shown in Fig. 7, using the latitude-longitude grid as a reference frame. The following results were obtained:

a. The motion of the hole in the cloud or the cloudless space located near 35°24'N, 111°53'W on pass 8 was computed to be 18.7 knots. The interval of time was 11.2 minutes.

b. The trailing edge of the well-defined cloud group located at approximately 35°21'N, 112°8'W on pass 8 was found to move at a speed of 18.8 knots with the time interval of 8 minutes between the two passes.

c. The leading edge of this same cloud group near 35°26'N, 112°8'W on pass 8 moved at a computed speed of approximately 25 knots within the time interval of 7.5 minutes. The average of the motion of the leading edge and the trailing edge was 21.9 knots which was also equal to the value found when the shadow instead of the cloud was used.

These computed values are in excess of the wind speeds reported from Flagstaff at 1341 MST for all levels below 30,000 feet. Since it is obvious that there was an increase in the cloud mass during the 8 minutes part of the computed motion must be attributed to this effect.

Similar computations were made on passes 11 and 12 (Fig. 8). Choosing cloud groups near the right-hand end of the two passes the following results were obtained:

a. The trailing edge of the cloud at 35°16'N, 111°25'W moved at a computed speed of 10-12 knots from 150 deg during 7 minutes.

b. The trailing edge of the cloud near 35°20'N, 111°25'W moved at approximately 10-12 knots from 150 deg during 7 minutes.

These values are somewhat smaller than those computed near the western boundary of the designated area. This variance may be due in part to the difference in topography of the two areas and also to the fact that the clouds selected were probably at different elevations and of different thickness.

As a check on these computed velocities another technique was used to determine cloud motion, which involved the use of cloud shadows with respect to a specific topographic feature on two consecutive frames. Since the interval of time between two consecutive frames is very short (32 sec), an error in measuring ground distance could result in relatively large errors when speeds are expressed in knots. Figure 11 shows two cases on which such computations were made. The speed of the shadow in (a) was found to be 14.7 knots and in (b) to be 13 knots. These two sets of pictures also illustrate that larger clouds, especially those with hard edges, change little in shape in short periods of time while smaller clouds, especially those with soft edges, show much change in periods as short as 32 seconds. The speeds computed in this manner from a number of cloud shadows along pass 2 are indicated by Fig. 12. These values are in close agreement with those determined by the first technique described and such a technique may be used to depict wind distribution over an area where direct observations are missing.

The clouds used for these latter computations were individual clouds or small groups of clouds separated from the large masses and they could be followed readily on two or three consecutive frames, but not over an interval of 5 minutes. Large clouds obliterate their shadows as well as those of smaller clouds in the vicinity. The cloud shadows were chosen only if they appeared distinctly in two consecutive frames and were not more than 10 naut. mi. from the principal line of flight.

Figure 13 shows the relationship of the rate of motion of the cloud and its shadow to the mean diameter of the shadow. Computations made on the individual clouds shown in Fig. 12 are plotted on the scatter diagram. There appears to be a definite relationship between the size of the cloud and the rate of motion. The larger clouds having been in their environment for a longer period of time than the small ones will tend to move at a faster rate. Also, they usually extend up to higher altitudes where the winds will generally be stronger.

The upper winds reported in the vicinity of the San Francisco peaks were as follows:

	Flagstaff 35°12'N, 111°40'W		Prescott 34°39'N, 112°26'W	Winslow 35°01'N, 110°44'W
	0844MST	1341MST	1100MST	1100MST
6000 feet			060-02 knots	340-10 knots
8000 feet	180-10 knots	180-09 knots	030-03 knots	340-11 knots
10000 feet	200-04 knots	210-12 knots	250-02 knots	030-06 knots
12000 feet	170-06 knots	200-03 knots	190-11 knots	060-03 knots
14000 feet	180-11 knots	270-04 knots	150-16 knots	170-03 knots
16000 feet			160-22 knots	150-07 knots
18000 feet			170-25 knots	160-18 knots
20000 feet	150-19 knots	230-03 knots	160-13 knots	150-20 knots
23000 feet			170-09 knots	130-14 knots
25000 feet	110-05 knots	150-12 knots		140-12 knots
30000 feet	170-13 knots	150-24 knots		140-08 knots

The cloud motion values computed by the different techniques previously described are well within the range of these wind speeds.

Byers and Braham (1949) found from data gathered in Ohio that the average speed of movement of radar clouds is less than the average of the wind speeds at all levels above the friction level. Clouds used for the computations in this study were in the early stages of development and probably could not be seen on radar so the rate of movement would not necessarily be comparable to that of radar clouds.

Computation of the height of cloud bases from several clouds and cloud shadows near the eastern boundary of pass 1 (1104 MST) gave 16,000 ft MSL. The radiosonde released from Flagstaff at 0844 MST recorded relative humidity values of less than 50% below 640 mb ($\approx$ 12,700 ft MSL), between 50% and 60% from this level up to 500 mb (19,200 ft) and became relatively dry above the 500 mb level. The 1341 MST sounding showed a slightly moist layer (50-68% RH) between 14,000 and 18,000 ft, a very moist layer (70-80% RH) between 21,000 and 26,000 ft, and relatively dry air above. The 1200 MST surface observation from Prescott (elev. 5,022 ft) reported scattered cumulus at 7,000 ft (≈ 12,000 MSL) and a second scattered layer with bases at 13,000 ft (≈ 18,000 MSL). Flagstaff (elev. 6,907 ft) reported scattered cumulus with bases at 5,000 ft (≈ 12,000 MSL).

6. Summary and Conclusion

From this study it has been shown that rectified U-2 cloud photographs provide useful data for research on the growth of convective clouds, the motion of clouds, and cloud distribution with respect to topography. With the development of the rapid and accurate photographic rectification technique a much greater number of already available U-2 cloud photographs can be turned into useful data. Reliable values of cloud movements can be computed by using either clouds or cloud shadows. The most consistent results, however, are obtained by using cloud shadows.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the participation of Mr. Harold Klieforth of the Experimental Meteorology Branch, Air Force Cambridge Research Laboratories, who planned the flight, and of Mr. Robbi A. Stuhmer, who assisted in assembling the mosaics.

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APPENDIX

A-1. Synoptic Situation

The large scale synoptic conditions on 25 July 1961 are shown in Fig. A-1. A high pressure ridge extends along 90W with one high cell centered over Alabama and another over the Iowa-Minnesota border. A slow moving E-W oriented front across southern Indiana, south central Illinois and central Missouri and Kansas joins with an occluded front from a low pressure center in Winnepeg to central South Dakota. Very weak cyclonic circulation dominates the southwestern part of the United States with one low pressure center over northern Mexico and another over the Nebraska-Wyoming-Colorado common border area.

The circulation aloft over the southwestern United States is dominated by a weak anticyclonic circulation. At the 700 mb level there is a narrow zone of weak convergence over Arizona.

A-2. Divergence Computations

Making use of observed winds the mean divergence over the Flagstaff network area was computed. Figure A-2 shows the comparative size of the area in question with respect to the location of available upper wind data. Mean vector winds through layers 2-4000 feet thick were used to compute the divergence from

$$D = \frac{1}{A}\frac{\Delta A}{\Delta t} \qquad (1)$$

The results showed that at 1100 MST small values of positive divergence of the order of 0.25×10^{-5} sec^{-1} were found below 14,000 feet. Between this level and 20,000 feet negative divergence values of approximately the same order of magnitude were computed.

A-3. Cloud Cover as Observed from the Ground

The hourly observations from Flagstaff indicate that the cumulus clouds began forming around 0900 MST with bases estimated at 5000 ft above ground or 11,900 ft MSL. The amount of cumulus increased steadily such that by 1100 MST a sky cover of 0.4 was reported. The observations were incomplete for the remainder of the day making knowledge on the continued growth of cumulus activity not available except from the U-2 photographs. Unfortunately the radar (ARG) from Flagstaff on this day was not in operation for the entire period of the U-2 flight. The radar was turned on between 0900 and 1035 MST and then after 1409 MST. Between 0900 and 1035 no cloud echoes were sighted on the radar screen. At 1409 MST when the radar was turned on, a distinct hook echo was observed near the 5-mile range marker northeast of the radar.

Prescott reported scattered Ac (0.1 sky cover) with bases estimated at 13,000 ft above the ground (18,000 ft MSL) throughout most of the day from 0800 MST onward. Cumulus with bases estimated at 9000 ft above the ground (14,000 ft MSL) began forming between 0900 and 1000 MST and continued increasing in amount until by 1400 MST the sky cover was reported as 0.6 Cb at 8000 ft and $<$ 0.1 Ac at 15,000 ft.

Winslow reported $<$ 0.1 sky cover of Cu at 8000 ft ($\approx$ 12,900 ft MSL) at 0800 and 0900 MST. By 1100 the cumulus clouds had evolved into cumulonimbus and the amount of cover continued to increase such that by 1600 MST it was reported as 0.6 Cb at 7000 feet.

A-4. Cloud Cover as Reported by U-2 Photographs

Figure A-3 shows the mosaics of the thirteen passes made by the U-2 between 1100 and 1345 MST. This depicts the increase in the amount of cloud cover over the designated area during the approximately two hours and forty-five minutes of aircraft operations as well as the effect of topography upon cloud growth. It appears that before the time of maximum solar heating the orographic effect plays the cominant role in the growth of cloud since the larger clouds appear first over the peaks. Near midday the effect of convective heating and orography are almost equalized.

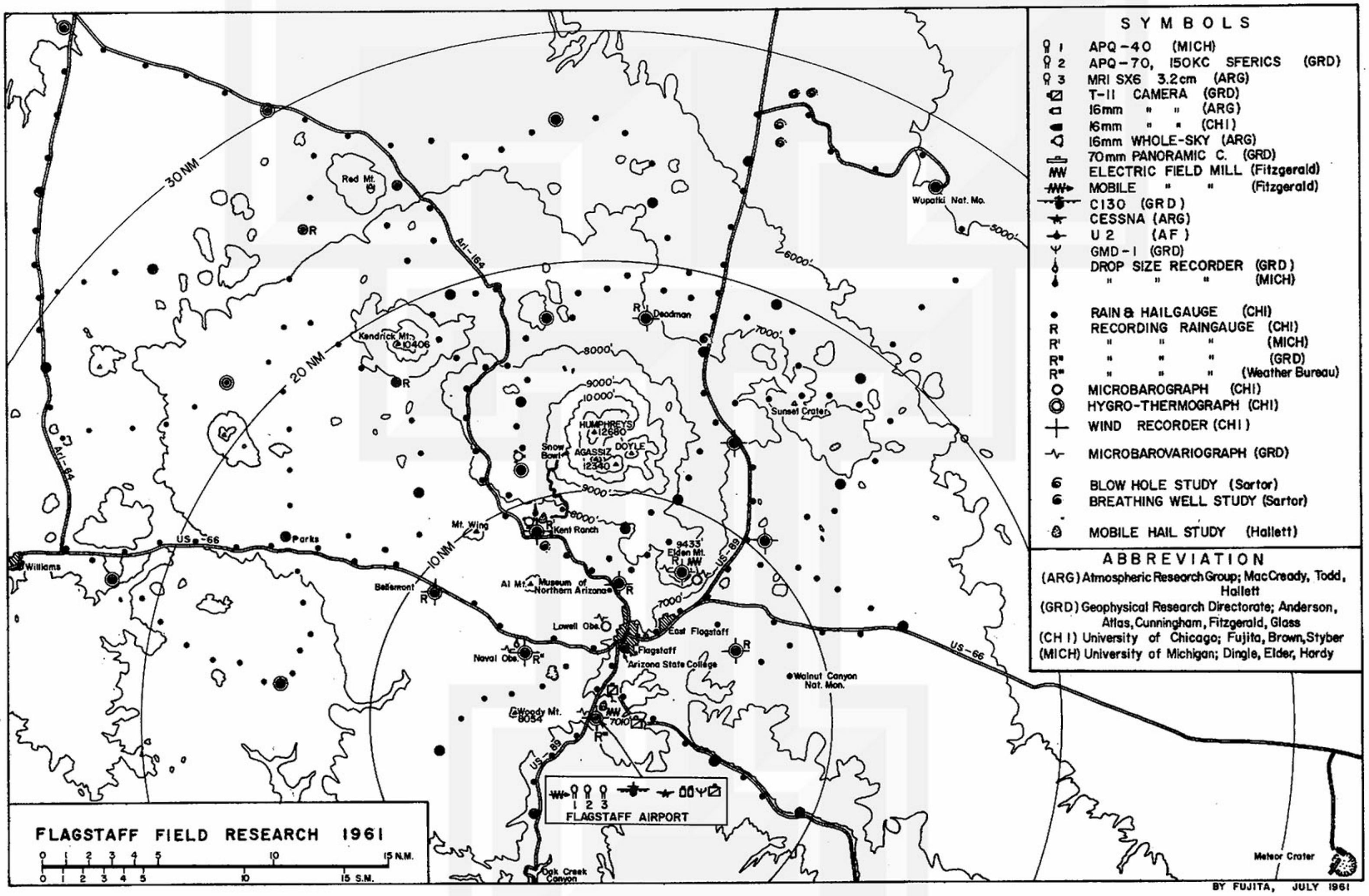


Fig. 1. Flagstaff Network, 1961.

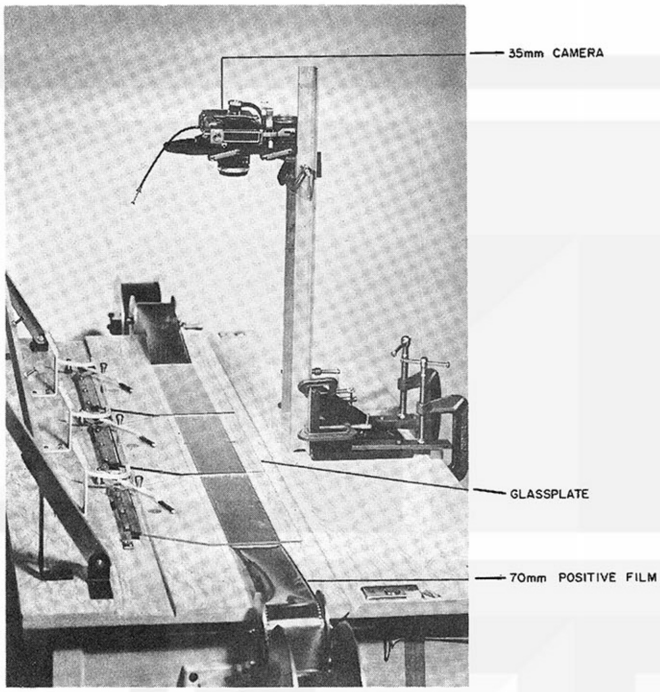


Fig. 2. The U-2 photograph analyzer and camera holder. The analyzer is capable of taking up to 1000 feet of the 70 mm U-2 film without cutting it. A roll of film is fed into the viewer with three glass plates which fix securely the relative positions of the proper rectification grids placed on three images.

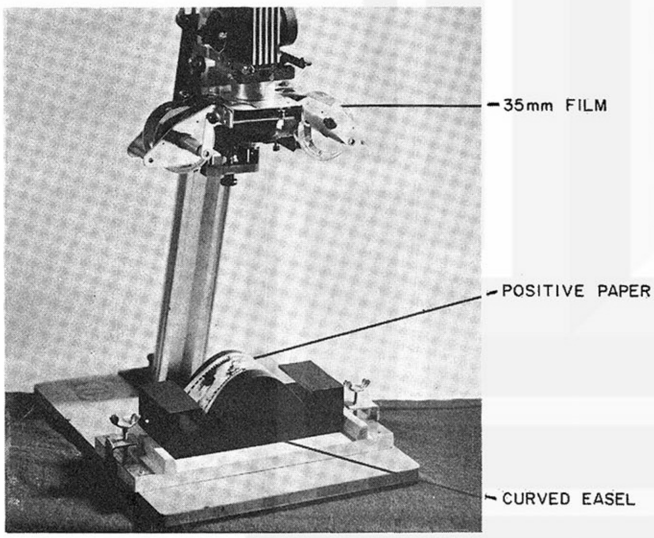


Fig. 3. Curved easel and enlarger used for cloud photograph rectification.

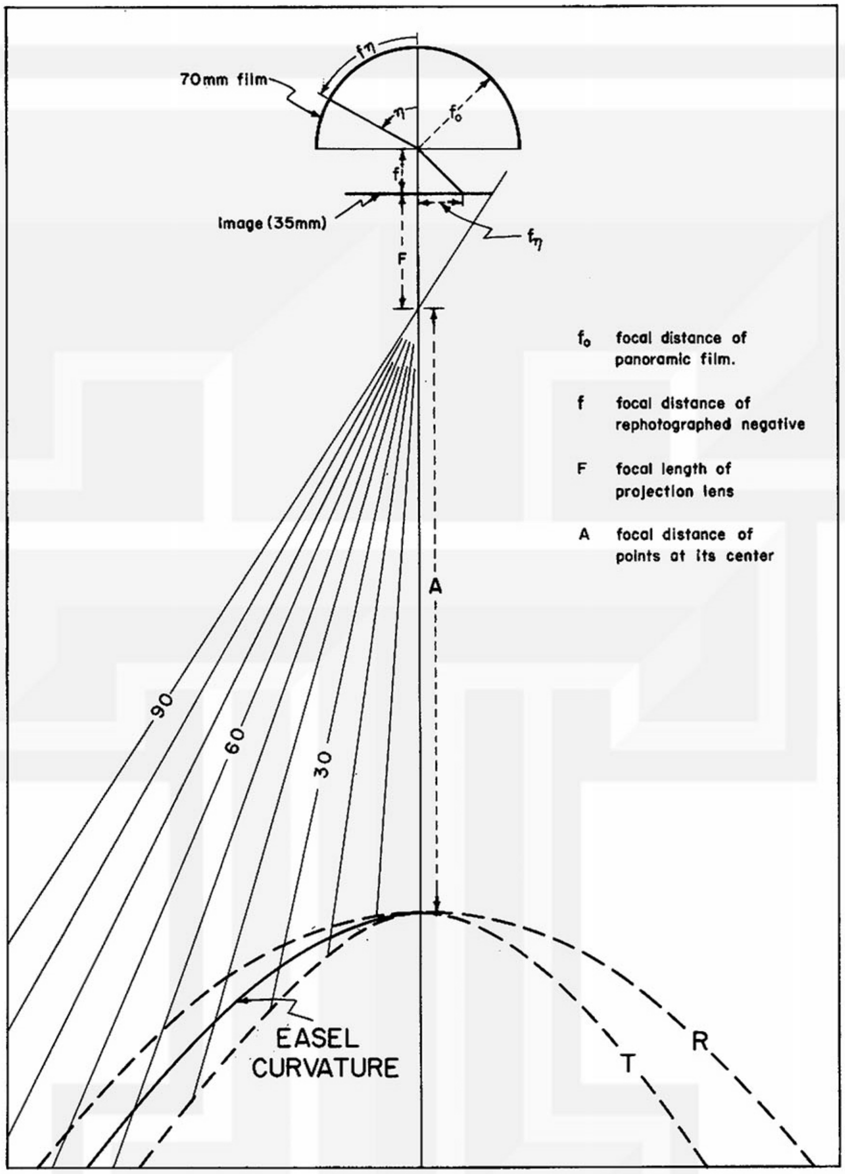


Fig. 4. Technique for determination of curvature of easel as a compromise between tangential (T) and radial (R) distortion.

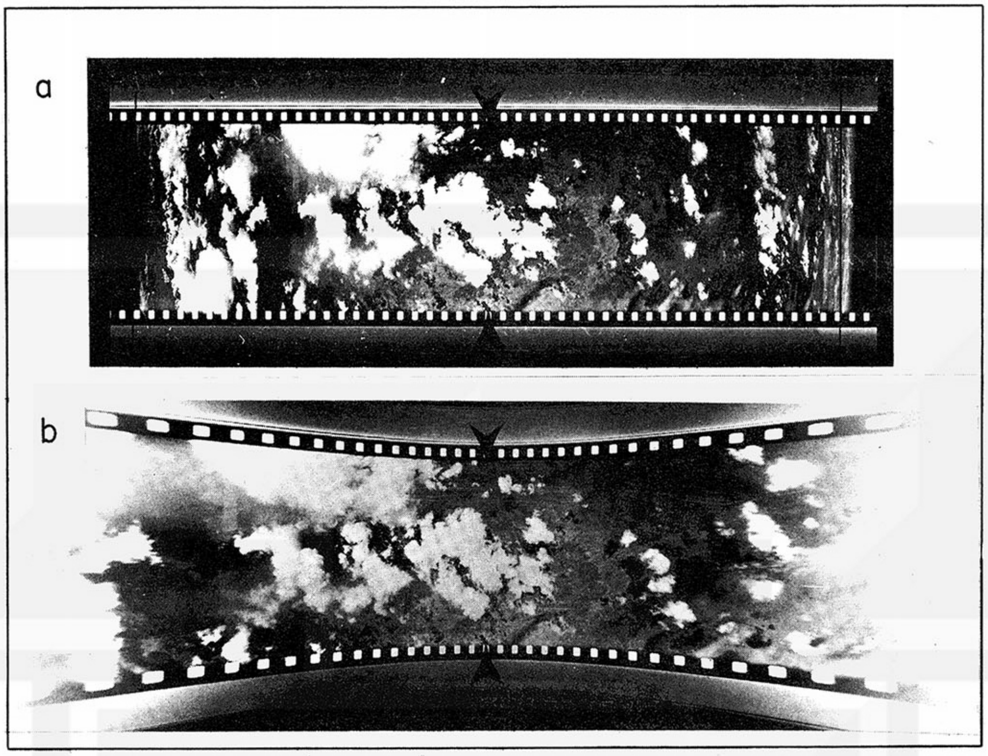


Fig. 5. (a) U-2 cloud photograph as displayed on 70 mm positive film. (b) Same photograph after rectification.

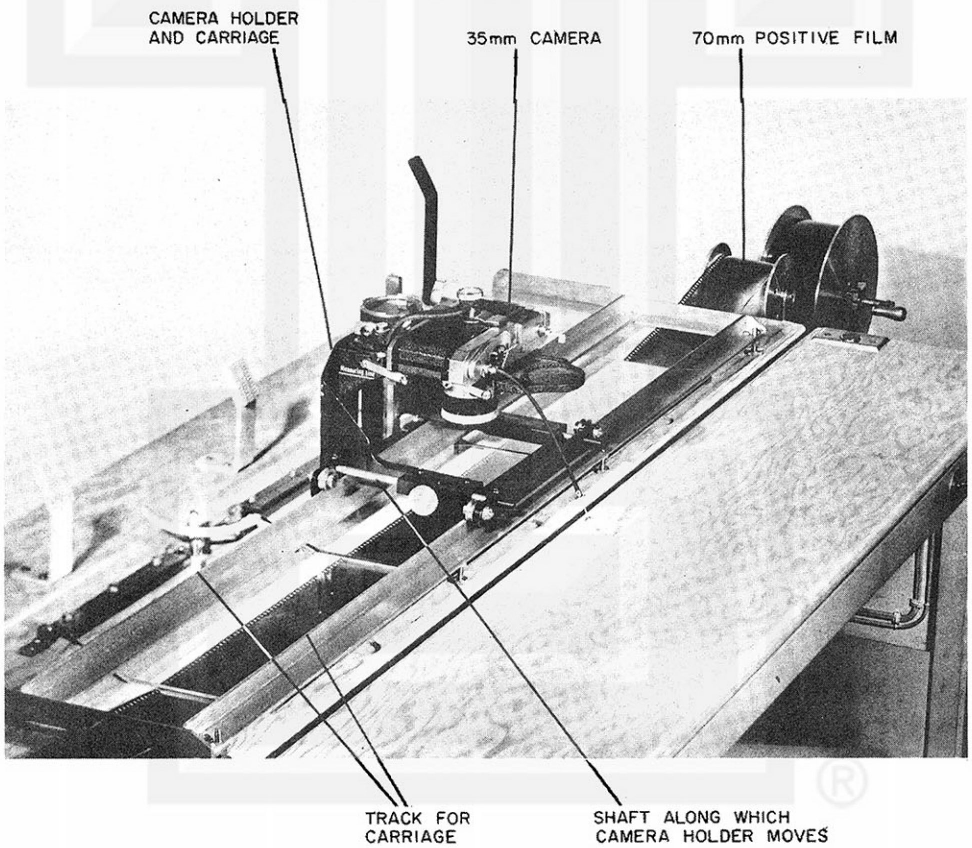


Fig. 6. The U-2 photograph analyzer and camera carriage used for photographing individual clouds on consecutive frames. The camera holder was mounted on a shaft so that it could move back and forth to cover the width of the 70 mm film.

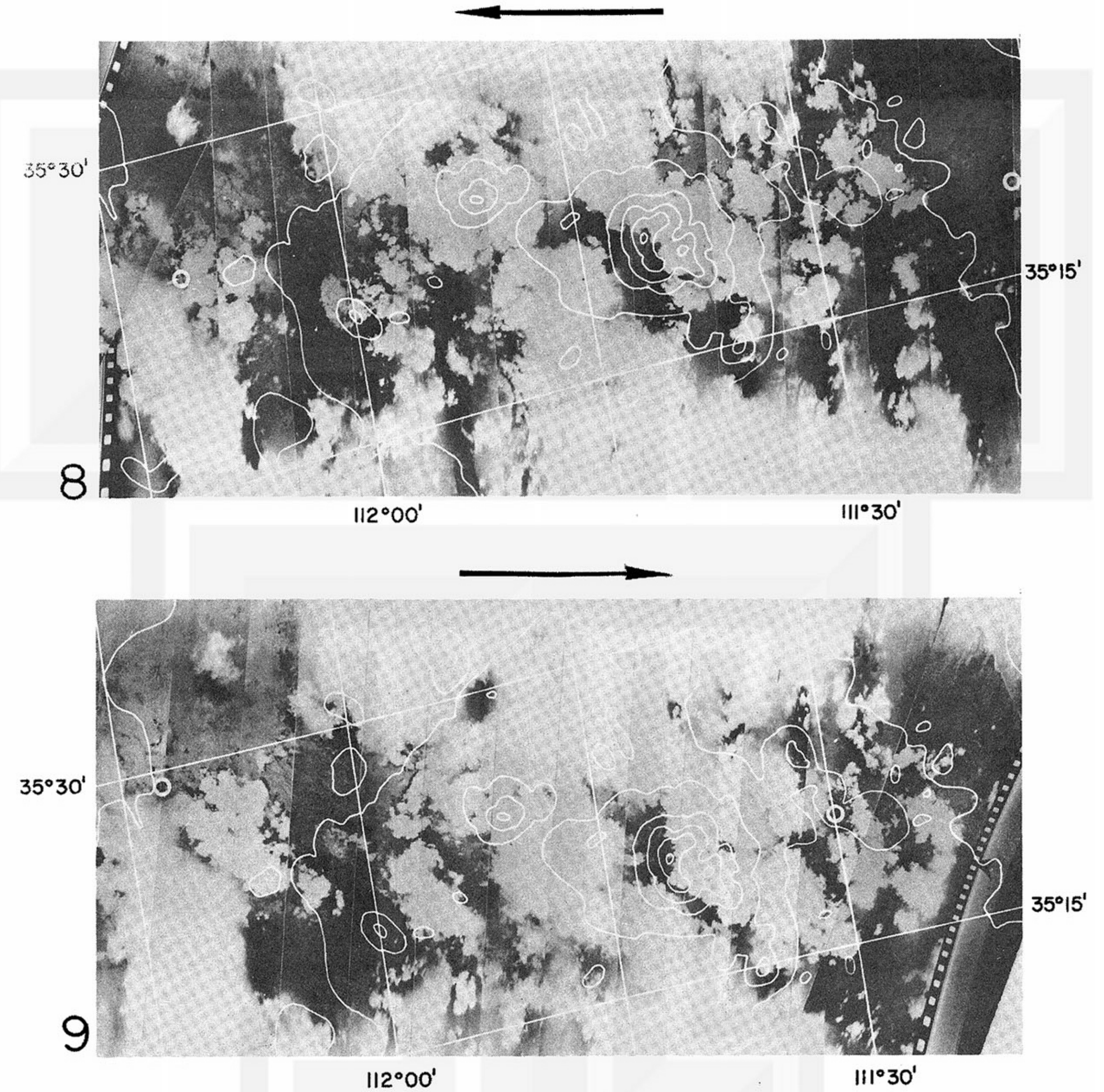


Fig. 7. Composite cloud photograph showing cloud distribution on passes 8 and 9. Arrows indicate direction of aircraft movement.

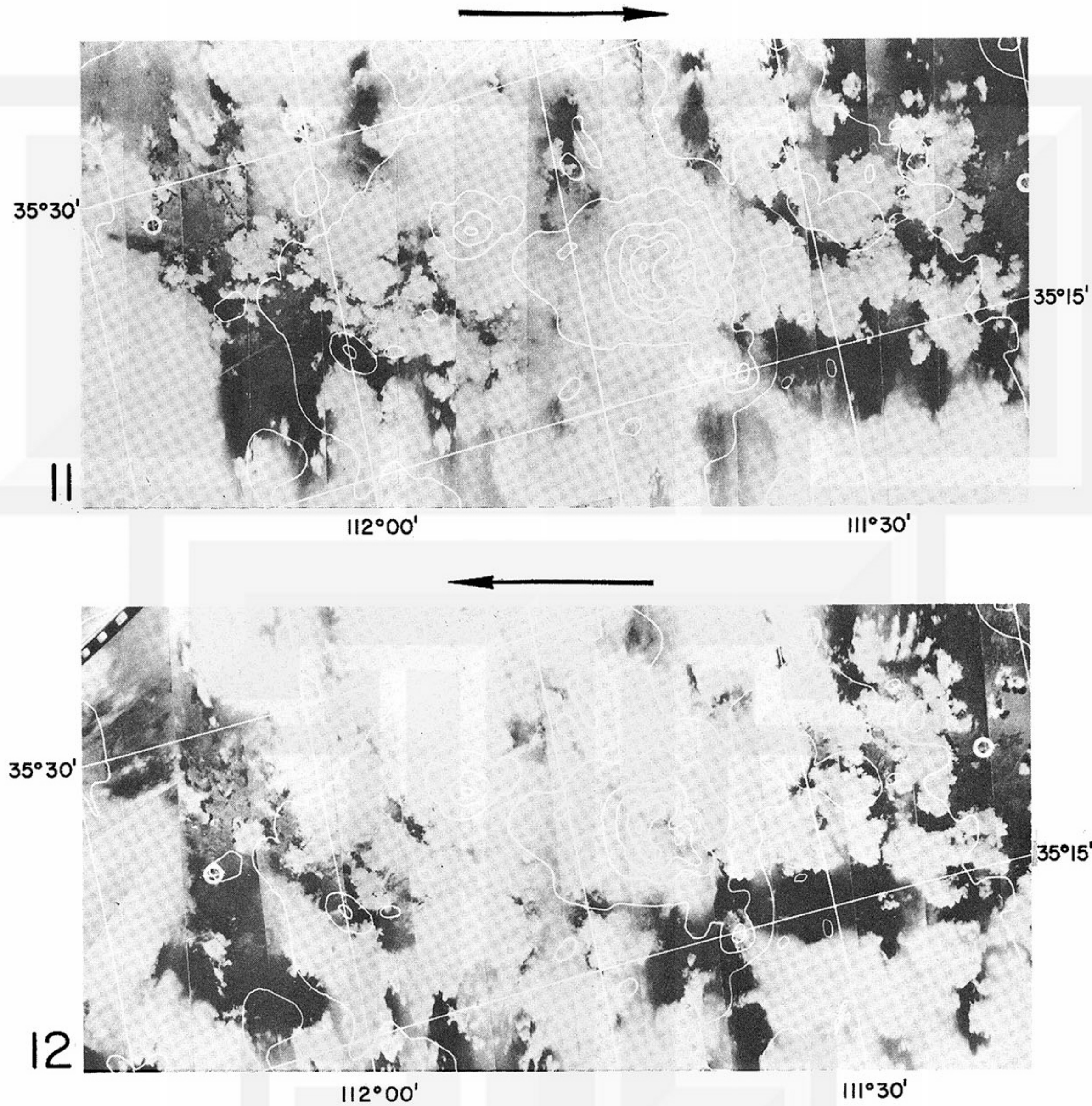


Fig. 8. Composite cloud photograph showing cloud distribution on passes 11 and 12. Time is approximately 34 minutes after that of Fig. 7. Arrows indicate direction of aircraft movement.

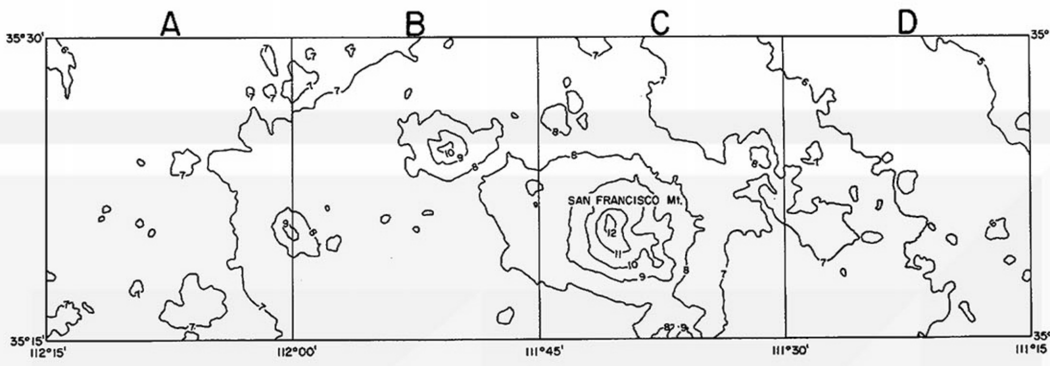


Fig. 9. Area over which cloud number and cloud area were computed. Contours are in thousands of feet.

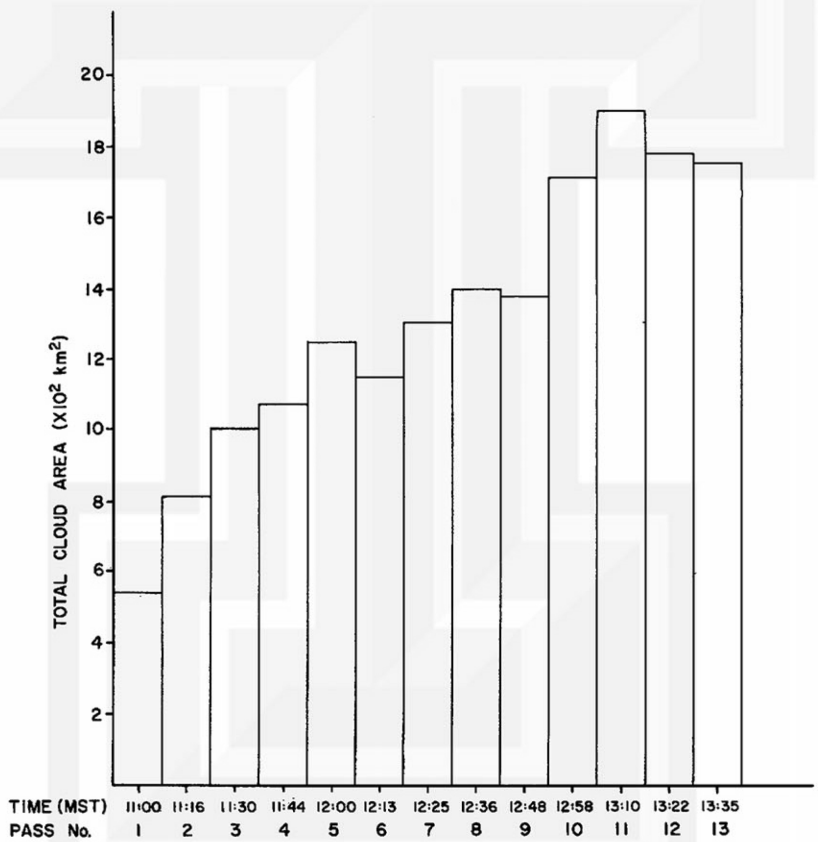


Fig. 10. Total cloud area in regions A, B, C, and D of Fig. 9. Time (MST) represents midpoint of the pass.

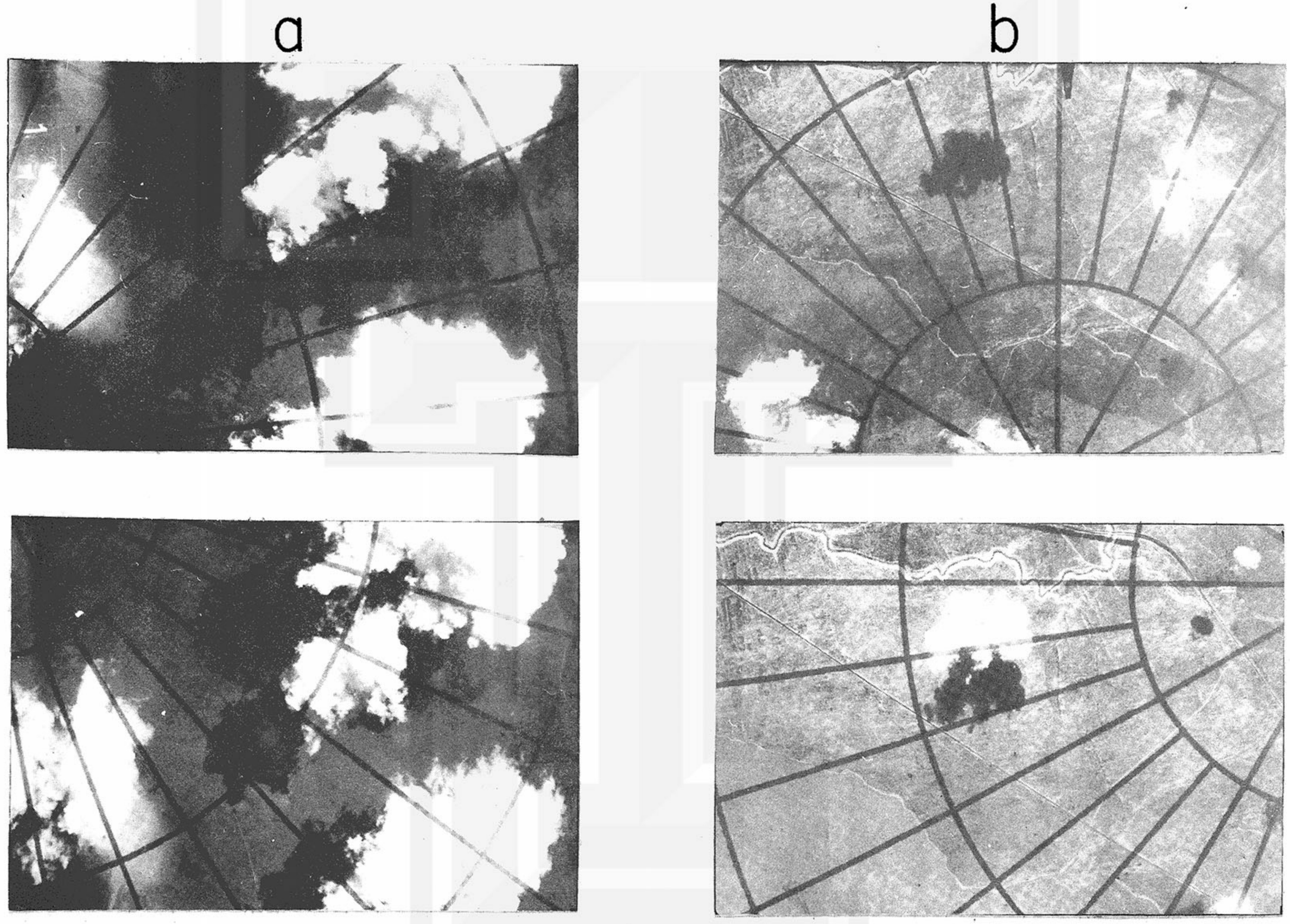


Fig. 11. Two cases of cloud shadows which are used to compute cloud motion. The two frames on the left (a) were taken near the middle of pass 1, and the two on the right (b) were at the eastern edge of pass 7.

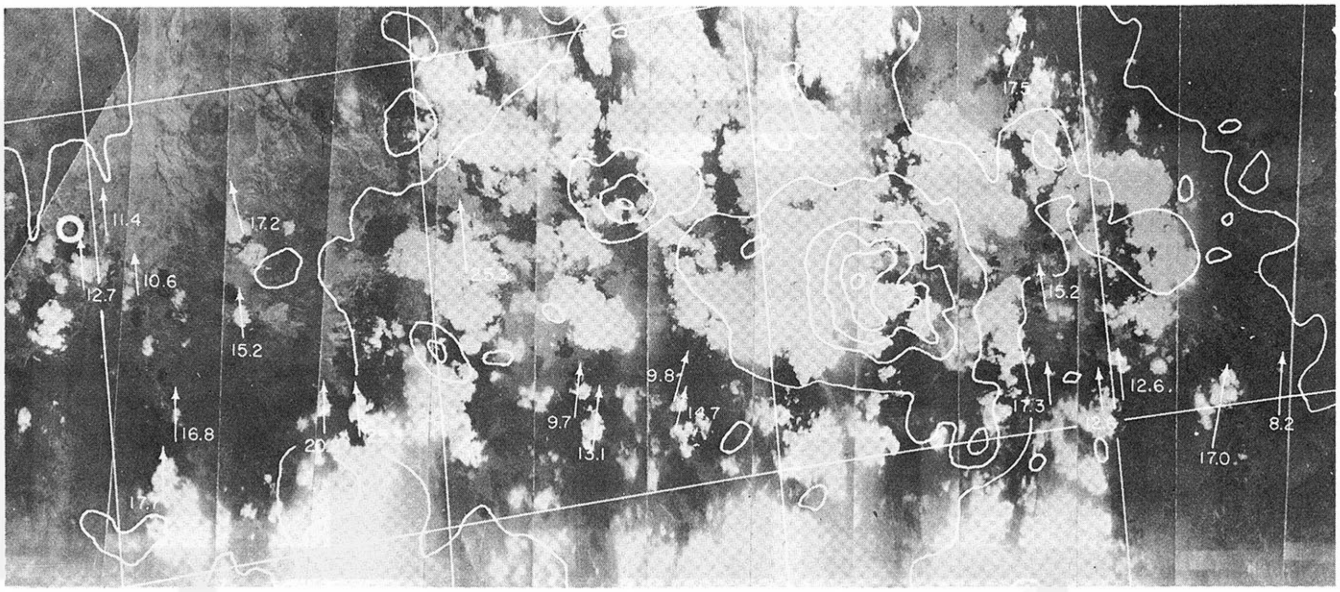


Fig. 12. Clouds chosen on pass 2 from which the motion of the shadows was computed from two consecutive frames. Arrows indicate direction of motion of shadow and number indicates rate of motion of shadow measured in knots.

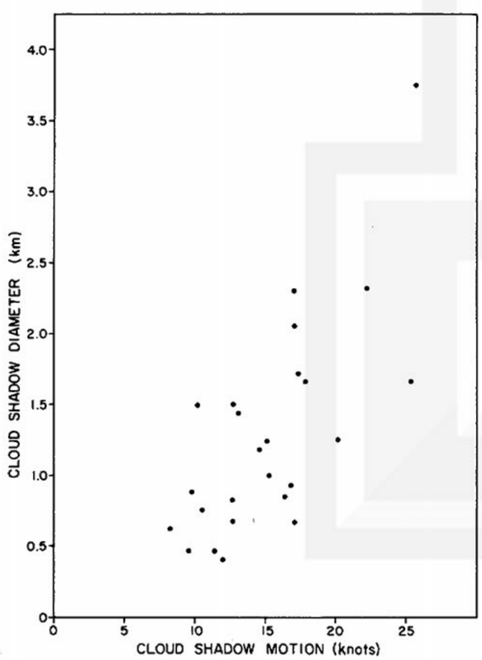
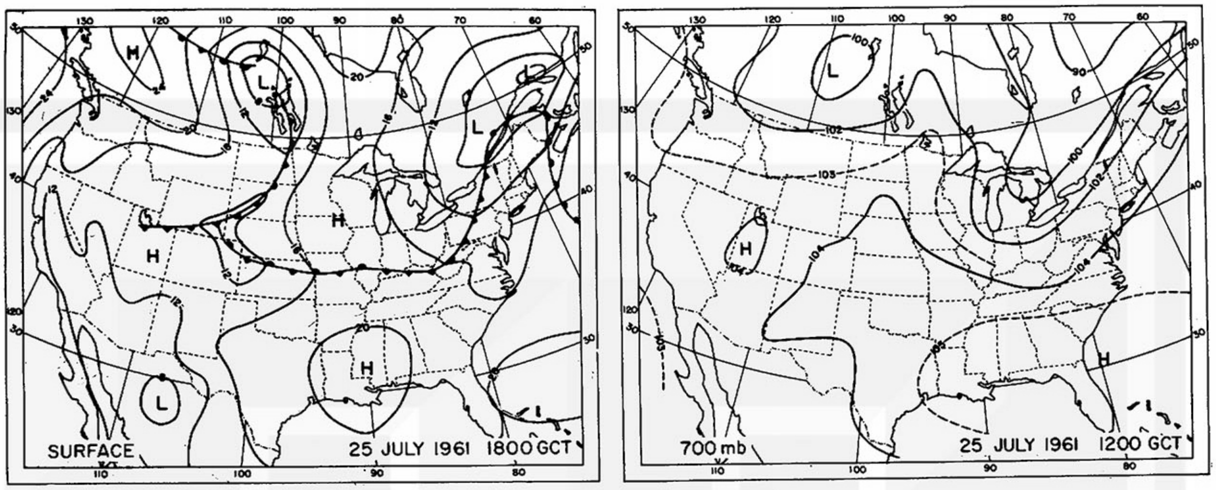


Fig. 13. Motion of cloud shadow as related to mean diameter of shadow. Clouds used for this graph are same as those in Fig. 12.



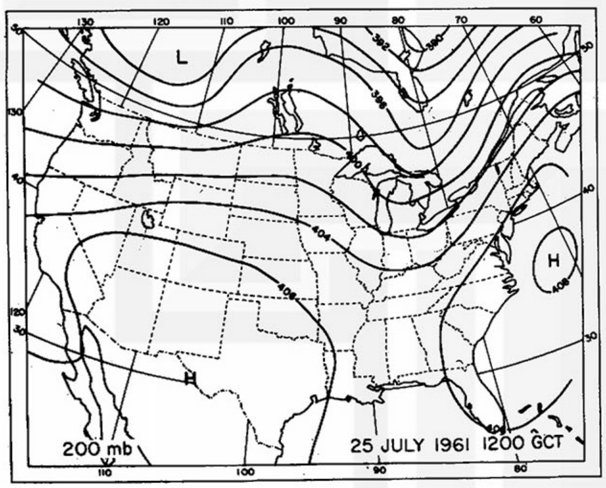


Fig. A-1. Synoptic charts for 25 July 1961 showing surface conditions at 1800 GCT (upper left) and 700 and 200 mb charts for 1200 GCT (upper right and lower left, respectively). Units on contours of upper air charts: hundreds of feet.

Fig. A-2. Area over which divergence computations were made. Dots indicate reporting stations for upper wind data. Small rectangle encloses Flagstaff network and roughly outlines area covered by U-2 cloud photograph mosaics.

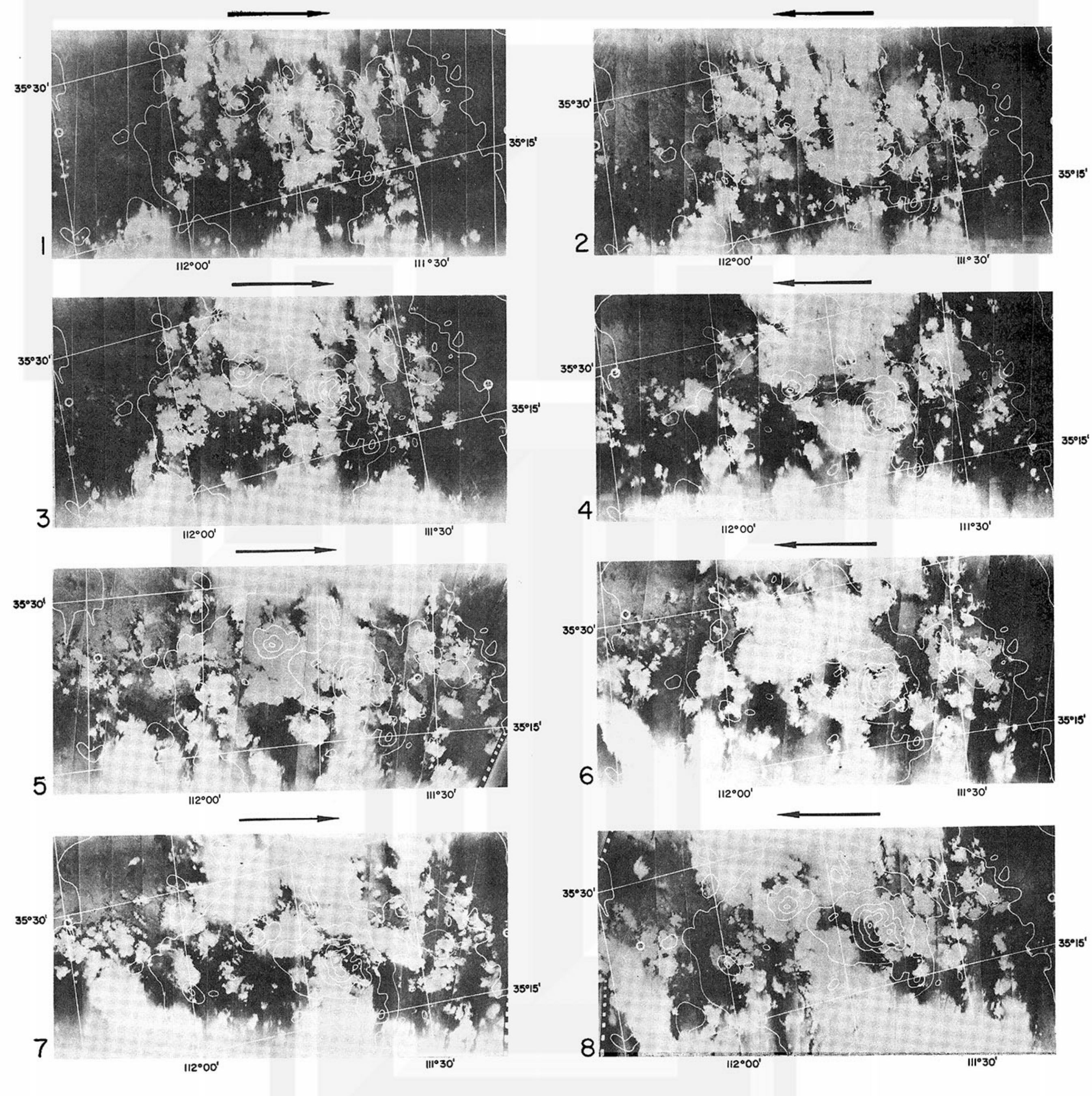


Fig. A-3. Mosaics of cloud pictures taken by U-2 with latitude-longitude grid and smoothed mean topography superimposed. Arrows indicate direction of motion of aircraft.

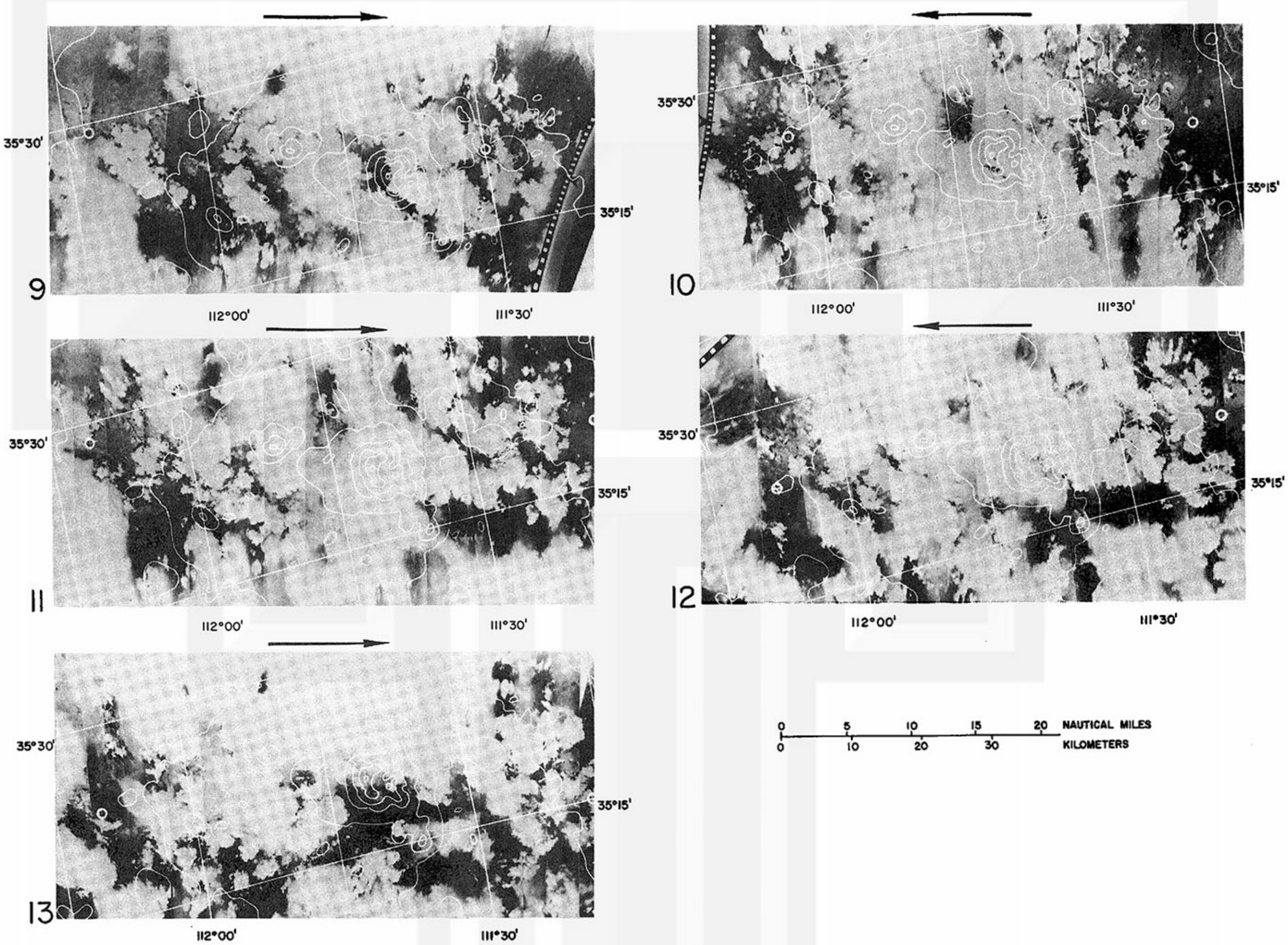


Fig. A-3. Continued.

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