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U.S. Weather Bureau.
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U. S. DEPARTMENT OF COMMERCE

U.S. WEATHER BUREAU

OFFICE OF FORECAST DEVELOPMENT

TECHNICAL NOTE NO. 13

THE USE OF METEOROLOGICAL SATELLITE DATA IN ANALYSIS AND FORECASTING

?

Donald M. Hanson

Office of Forecast Development

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TIROS Satellites and Satellite Meteorology

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THE USE OF METEOROLOGICAL SATELLITE DATA IN ANALYSIS AND FORECASTING

I. INTRODUCTION

A. Background

Cloud data currently available from TIROS-type satellites contain abundant information on clouds of all scales ranging from very large-scale patterns down to scales smaller than those which can be observed from a fixed network of ground-based stations of a density like that over the United States. From the point of view of the practicing forecaster, the nature of the contribution of satellite data varies somewhat from place to place. This variation depends on: 1) the geographic distribution, frequency, and completeness of conventional observations, and 2) the nature of the forecast problem being dealt with. The forecaster in the Midwestern United States, for example, who might have forecast responsibility for a two-state area, has considerable large-scale cloud information available from the three-hourly facsimile Weather Depiction and Radar Summary charts, hourly observations, etc. On the other hand, he has very little information on small-scale structures, knowledge of which is necessary for making detailed forecasts for specific cities and airports. While the satellite gives this Midwestern forecaster additional information on the large-scale systems, its greatest contribution for him is in the smaller scale, since it is in this scale that the conventional data are most deficient.

On the other hand, the forecaster who has responsibility for generalized marine forecasts for the North Central Pacific has inadequate information on cloud systems of all scales. But since his need is mostly for broad-scale cloud patterns, this is where the greatest contribution of satellite data lies for him.

Related to the question of scale is the question of timeliness of receipt of the data by the forecaster. The usefulness of large-scale cloud information diminishes relatively slowly with time because of the temporal stability of these patterns. On the other hand, data on small-scale systems must be placed in the hands of the forecaster quickly in order to be of maximum use because of the shorter lifetime of these small-scale structures.

From this point of view, the direct readout (DRO) capability being planned for operational satellites should be very useful. The addition of this feature will enable the forecaster to acquire directly from the satellite, photographs covering an area some 1,000 miles on a side in the vicinity of the forecaster's station. The photograph suitable for use in making detailed, short-period forecasts will reach the forecaster within five minutes of the time it is taken. This photograph, received immediately will be in addition to the currently available schematic nephanalyses covering broad geographic areas, but reaching the forecaster somewhat later. The nephanalyses are especially useful in the larger-scale problem.

B. Purpose

This paper attempts to summarize what is known about the use of satellite data in analysis and forecasting. It is directed primarily to the U. S. Weather Bureau forecast community. There are obvious risks involved in such an undertaking. Since this is a new field, conclusions which we have drawn today may be shown to be obsolete tomorrow. But because this is a new, rapidly developing field, there is a great need for pulling together what seems to be known about the practical application of satellite data now.

The paper represents an organization and synthesis of extracts, digests and summaries of papers, both published and unpublished. The fact that reference is made to one author and not to another who has written on the same subject carries no specific implication regarding the relative contribution of the authors. It merely indicates that one paper was more readily available than another.

During the past three years, forecasters have been able to accumulate some experience in using nephanalyses. However, when DRO becomes operational, many forecasters will be seeing current cloud photographs for the first time. Therefore the emphasis in this paper is decidedly on the operational use of photographs. However, since the nephanalysis is simply an interpretation of the photograph, there is included by implication suggestions on the use of that portion of the information included in the nephanalysis.

While the ultimate usefulness of any meteorological data is the degree to which they help in making a description of the state of the atmosphere, it would seem useful to separate the current practical contribution of satellite cloud data into two parts. One of these contributions is the inferences that can be drawn from the cloud data concerning circulation, static stability, air mass boundaries, moisture content and the like. This is best done (but not exclusively so) in terms of the large-scale structures. The other contribution is a direct one which involves extrapolating past and present cloud patterns into the future. This is most appropriate (although not exclusively so) in terms of the smaller-scale structures involved in making short-period, detailed forecasts of clouds. This paper attempts to deal with both of these contributions.

II. SOME CHARACTERISTICS OF SATELLITE PHOTOGRAPHS

A. Fidelity

The factors which determine how well the photograph shows what is actually being photographed are to be found in both the optical and electronic portions of the camera system and in the altitude and attitude characteristics of the satellite (Stroud 1961). Among these factors are lens distortion, focus, image contrast, width of the raster lines, electronic "noise", and the distance from the "target" to the camera.

Erickson and Hubert (1961, P. 21) summarize the practical effects of these factors in the TIROS wide angle camera system by saying that individual fair weather cumulus clouds (diameter near ½ mile) cannot be resolved in the photographs, towering cumulus (diameter ½ to 2 miles) may or may not be resolved, while an isolated mature thunderstorm (diameter 5 to 10 miles) will be visible on the photograph unless it is near the horizon.

B. Perspective

One problem in perspective arises from the fact that the view of the spherical earth is of necessity presented on a plane surface. The resultant "foreshortening" is aggravated by the oblique angle with which the space-oriented TIROS camera is viewing the earth. Foreshortening is eliminated from the nephanalyses produced at the Weather Bureau Satellite Stations at Wallops Island, Virginia, Point Mugu, California, and Fairbanks, Alaska. For users of the direct-readout photos from the operational DRO system, this problem will be considerably diminished, since the camera will always be pointed directly toward the earth.

Other problems in perspective are discussed by Erickson and Hubert (1961, pp 29-30). These arise from the fact that there are sometimes differences between the view of clouds systems from the satellite and that gained from reports of ground observers. These differences arise partly from the differences in resolution between the human eye and the satellite camera system. But perhaps more important are other factors, such as the relatively limited field of view of the ground observer and the method of reporting what the ground observer sees.

Some of these differences are schematically illustrated in figure 1. Figure 1a shows a sharp edged cloud mass, which both the satellite and ground observer may view as such. But because of the method of reporting sky cover, ground based reports show a gradual transition across the boundary from clear, through scattered and broken, to overcast. Figure 1b is intended to show isolated cloud masses, such as towering cumuli, which occupy less than half of horizontal space (scattered) when viewed by the satellite overhead. However, because of vertical development, the observer on the ground is able to see less of the sky through the clouds, and usually overestimates the amount of cloudiness.

III. SYNOTPIC SCALE USES OF SATELLITE CLOUD DATA

This section is concerned with interpretation of large-scale cloud patterns in terms of synoptic scale circulation features and large-scale air mass characteristics. Since conventional data are more deficient in this regard over ocean areas than land areas, the emphasis here is on application over oceans.

A. General.

Over the years, there has evolved a number of rules-of-thumb which have been effective in making weather forecasts from prognostic flow patterns

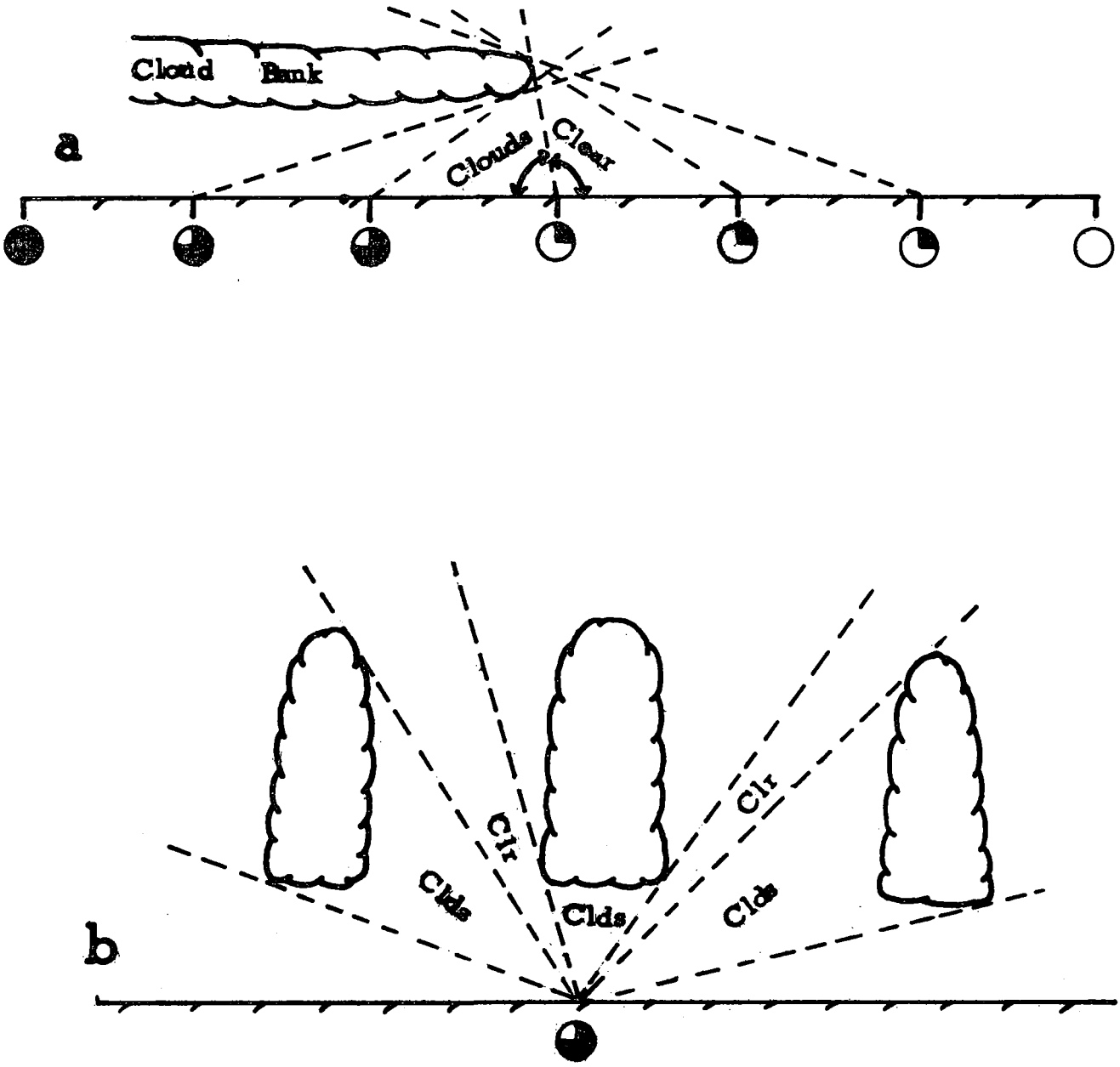


Figure 1. Schematic illustration of difference in perspective between satellite and ground observer.

(for example Oliver and Oliver, 1945). These rules can be turned around and used for deducing the flow from observed cloud patterns. A few of these are stated as follows:

1. In the region of the mid-latitude westerlies, the main cloud masses will lie between the mid-tropospheric trough and the downstream ridge. The relatively cloud-free area will lie between the ridge and the downstream trough. A modernized version of this rule (Dunn, 1962) would be that in major cloud systems the mid-tropospheric vorticity advection is most likely positive (increasing upstream). In large relatively cloud-free areas the vorticity advection is most likely negative.

2. Where a band of frontal clouds extends well into the cold side of the surface frontal position, the flow aloft is roughly parallel to the front. Where the frontal clouds are on the warm side of the surface frontal position or are absent, the flow aloft is across the front from the cold to the warm side.

3. When there is rapid west to east motion of the main cloud system, as seen on successive satellite passes, the flow aloft is likely to be quite strong and of low amplitude. When the motion of the cloud systems is more meridianal, the westerlies are likely to be of large amplitude.

4. Where an extensive area of low clouds lies along the slopes of mountains with a sharp edge of the clouds near the peak of the ridge, the low level flow is upslope.

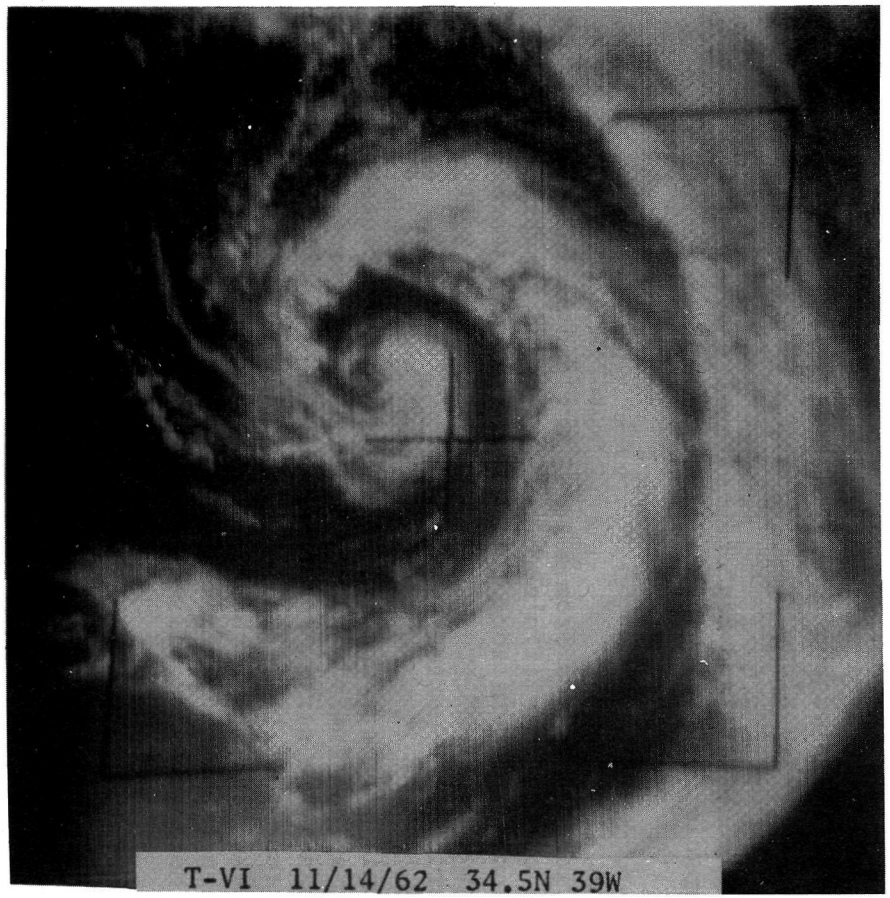
5. Over ocean and flat land regions, extensive areas of low clouds will be accompanied by cyclonic low-level flow.

B. Vortices.

The detection of cyclonic vortices from satellite cloud pictures is perhaps the most spectacular of the satellite's contributions to synoptic meteorology. It is a fortunate circumstance that these cyclonic storms, being among the most important weather producers, mark themselves most clearly by their characteristic cloud patterns.

In most cases, cyclonic vortices are easily recognizable because of the bands of clouds that spiral inward in a cyclonic sense toward a center. At times the cloud bands are narrow and separated by broad clear areas. At other times the bands tend to merge into an almost solid cloud mass, but with darker streaks visible which spiral inward. The more usual case lies somewhere between these two extremes. Two examples of vortices are shown in Figure 2. More examples will be shown later.

Experience thus far has indicated that well defined vortices in cloud patterns are in the vast majority of cases associated with cyclonic circulation patterns. In a few cases, perhaps because of inadequate supporting



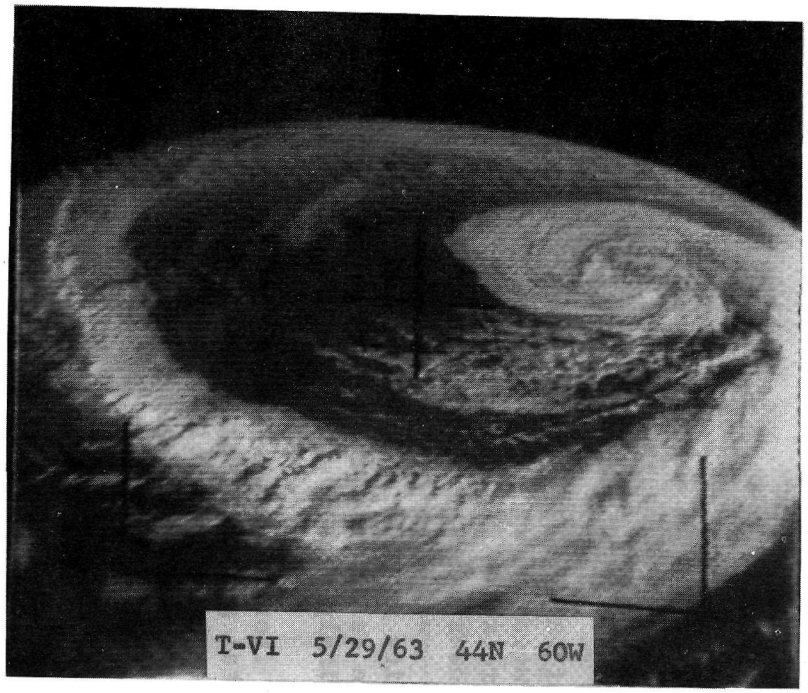


Figure 2. Two examples of vortices as photographed by TIROS satellites.

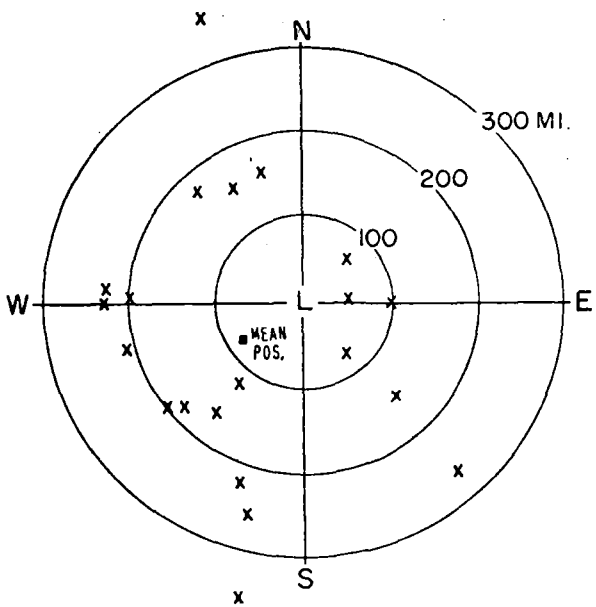


Figure 3a. Position of 21 TIROS vortices with reference to associated sea level low center in the northern hemisphere.

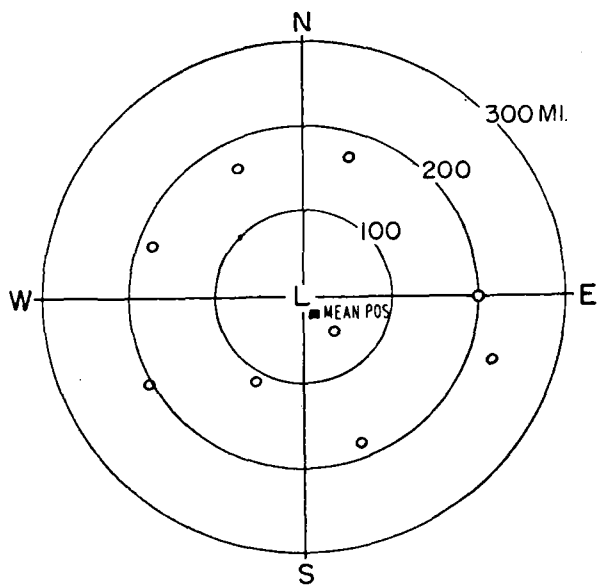


Figure 3b. Position of 9 TIROS vortices with reference to associated 500-mb low center in the northern hemisphere.

(After Boucher and Newcomb, 1960)

conventional data, cloud vortices were associated with no identifiable circulation vortex. But in some of these instances, a related circulation vortex was identified later on. In a small number of cases the cloud vortex was better identified with a vortex in the wind shear field (thermal wind) than with the wind itself. These matters are currently under investigation. The fact remains that in the great majority of cases the cloud vortices are associated with circulation vortices.

Boucher and Newcomb (1960) have used a somewhat limited sample of data to show the correspondence between the location of centers of cloud vortices and the centers of atmospheric circulation. Their results are shown in Figure 3.

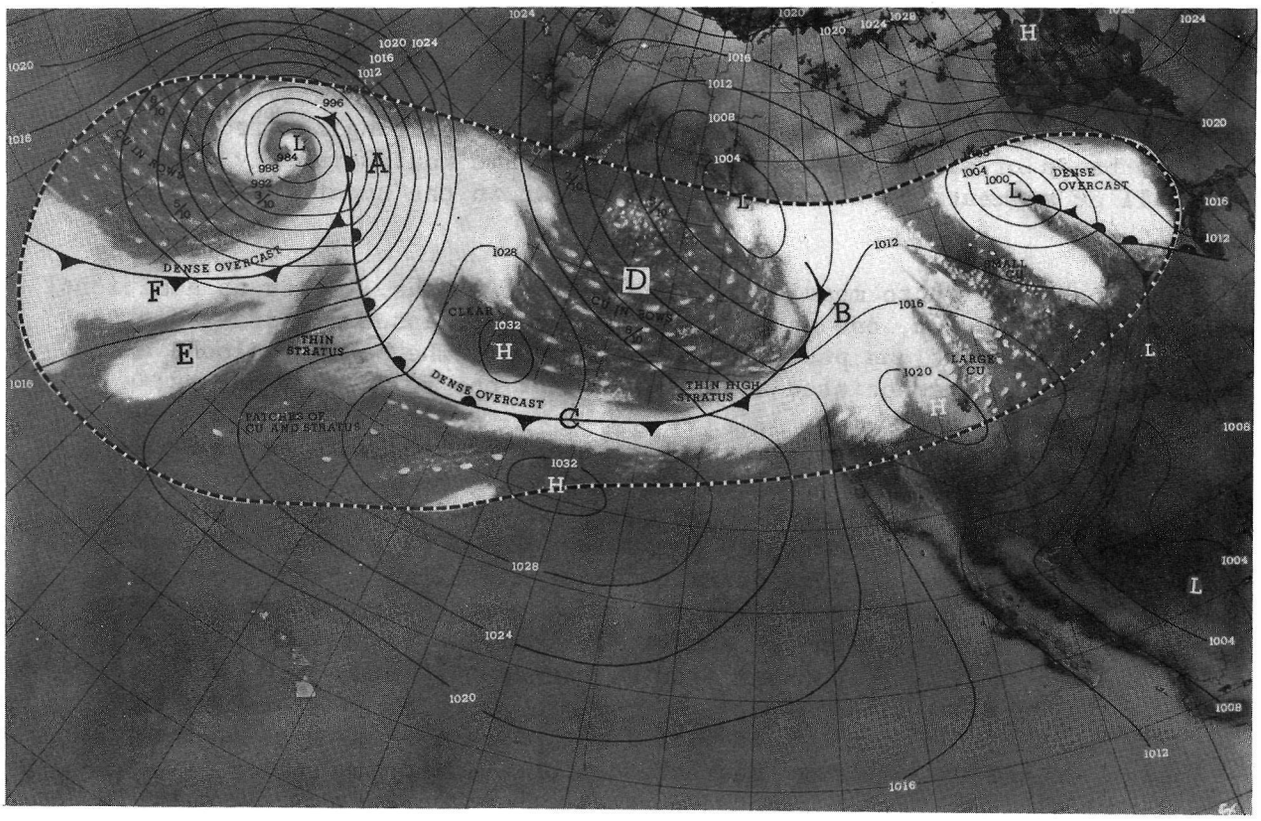
These data suggest that in the absence of contrary indications from conventional data, the surface low is best located some 100 miles northeast of the cloud vortex, and the 500-mb. low coincident with the vortex in the northern hemisphere. These results must be considered tentative, pending current efforts to enlarge the sample.

Wave cyclone vortices will be dealt with in more detail in the following section (III-C). Tropical cyclone vortices will be dealt with in the subsequent section (III-D).

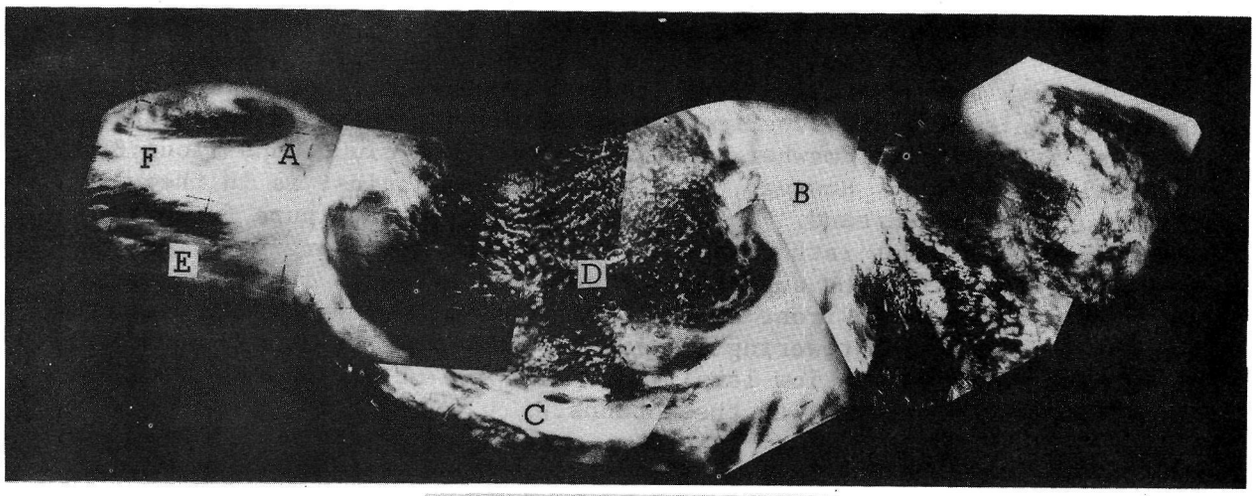
C. Fronts and Cyclones.

According to synoptic models, fronts are associated with bands or zones of cloudiness. In the classical examples cold fronts are usually associated with relatively narrow bands of clouds and warm fronts are associated with more extensive regions of cloudiness. While it is true that there have been a number of instances where "front-like" bands of clouds have existed where no front has appeared on conventional synoptic analyses, the forecaster is cautioned against minimizing their importance. The existence of these bands implies either the current or recent existence of organized upward motion. That this upward motion is ascribed to some other process rather than frontal lifting does not diminish its practical importance.

The lower portion of Figure 4 is a mosaic made from individual photographs from several consecutive orbits. With this broad view available, the frontal pattern becomes quite evident, partly because of the perspective provided by the broad coverage and partly because this appears to be a classic situation in which the actual cloud patterns closely resemble the Norwegian Model. The situation represents a polar front system with its series of cyclones. Cloud systems associated with relatively mature wave cyclones are represented by areas A and B with the connecting and trailing fronts by bands C and F. The area labeled D is covered by a cold unstable post-cold front air mass. In this area ship reports suggest greater cloud coverage than seems apparent from satellite data. This can probably be attributed to the differences between the perspective of the satellite and that of the observer on the earth's surface, as illustrated



STORM FAMILY OVER THE NORTH PACIFIC OCEAN
TIROS CLOUD PICTURES SUPERIMPOSED ON CONVENTIONAL WEATHER MAP



ACTUAL TIROS PHOTOGRAPHS TAKEN ON MAY 20, 1960

Figure 4. Synoptic map, TIROS photo mosaic and nephanalysis for the North Pacific. May 20, 1960. (After Oliver).

in Figure 1b. Area E shows what are probably low stratus or stratocumulus clouds and possibly even some fog formed as the warm tropical air flows northward over colder water on the west side of the subtropical anticyclone. It should be pointed out that the distinction between areas E and F on the photo mosaic is such that there is little doubt that area F rather than area E is associated with the polar front.

Given even small segments of the photo mosaic, there probably would be little difficulty in this clear-cut situation of placing the frontal systems on the basis of satellite photographs. The same would probably hold true for all or segments of the nephanalysis shown in the upper portion of Figure 4.

Figure 5 shows a photo mosaic from the Gulf of Alaska. Given no additional synoptic information, one can with some degree of assurance draw some conclusions from the cloud photographs themselves. The band of clouds along BC is very likely associated with a front for the following reasons:

1. The band exhibits characteristics similar to those shown in area C of Figure 4. These characteristics are the rather solid and uniform character of the cloud mass and its organization as a long band but narrow in comparison with its length. While the cloud mass along DE appears to be of a similar texture to that of BC, it is not organized as a long, rather narrow band. Fritz (1961) and Erickson and Hubert (1961) identify mass DE as the precursor of an upstream frontal wave.

2. The cloud pattern in vicinity of area A strongly suggests the presence of a vortex, characteristic of a mature cyclone. A cold or occluded front oriented north/south or northeast/southwest to the east of the mature cyclone such as represented by the cloud band along BC could be expected. The corresponding National Meteorological Center (NMC) surface analysis indicated that this was indeed a front.

Figure 6 shows a single frame from TIROS I viewing the Eastern North Pacific. Neglecting the superimposed surface observations and isobaric analysis, it would be somewhat tempting to call the cloud band along BB a frontal cloud band. However, a strong argument against is in the very texture of this cloud band. In contrast to band BC in Figure 5, this band is not solid, but rather appears as a rather loose organization of cloud elements. From the superimposed analysis and data it can be seen that there is indeed no front in the area, but rather the cloud system is made up of cumulus and towering cumulus clouds with a tendency toward banding perpendicular to the low level flow. The 700-mb and 500-mb flow, however, were nearly parallel to these bands.

Boucher and Newcomb (1960) present a preliminary series of cloud models related to wave cyclone development for use in synoptic interpretation of satellite cloud photographs.

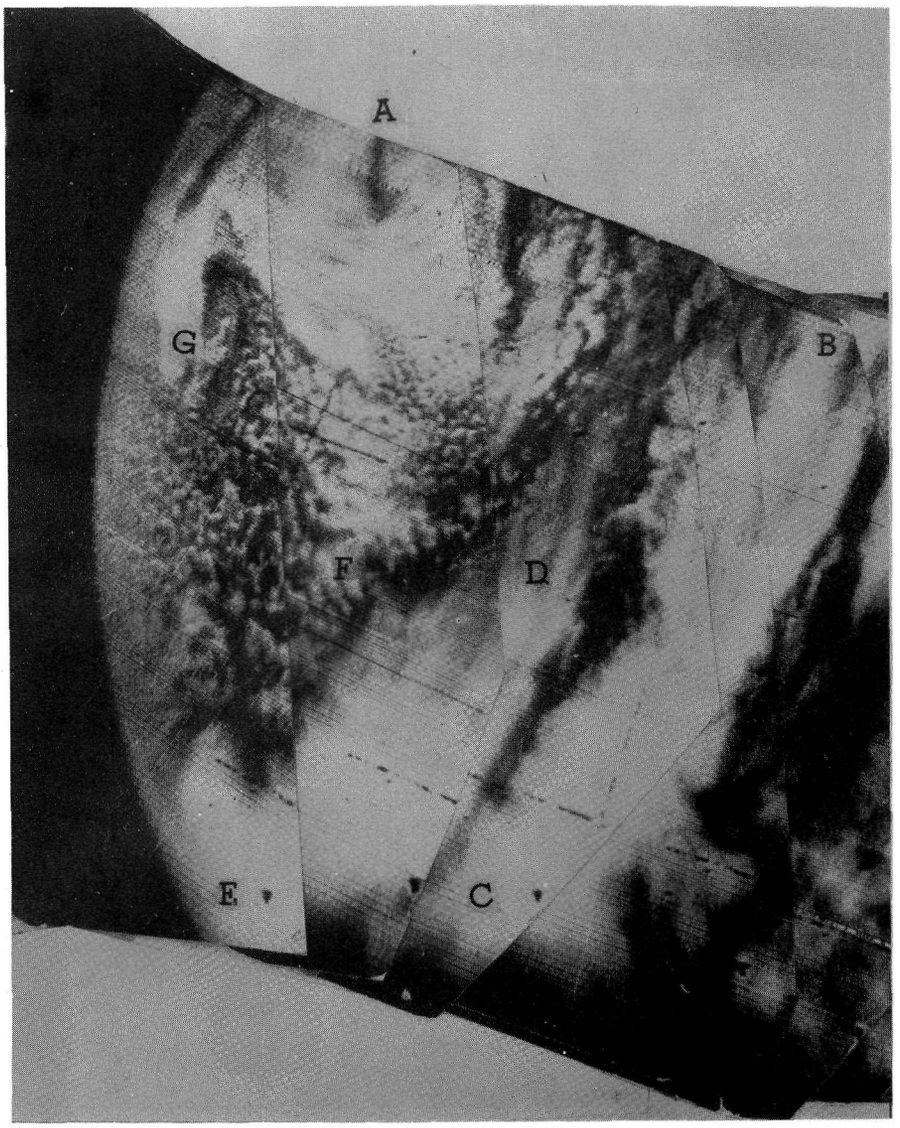


Figure 5. Composite picture of Gulf of Alaska storm features. Pictures were taken at approximately 2200 GMT 1 April 1960. (After Fritz, 1961, further studied by Winston & Tourville, 1961)

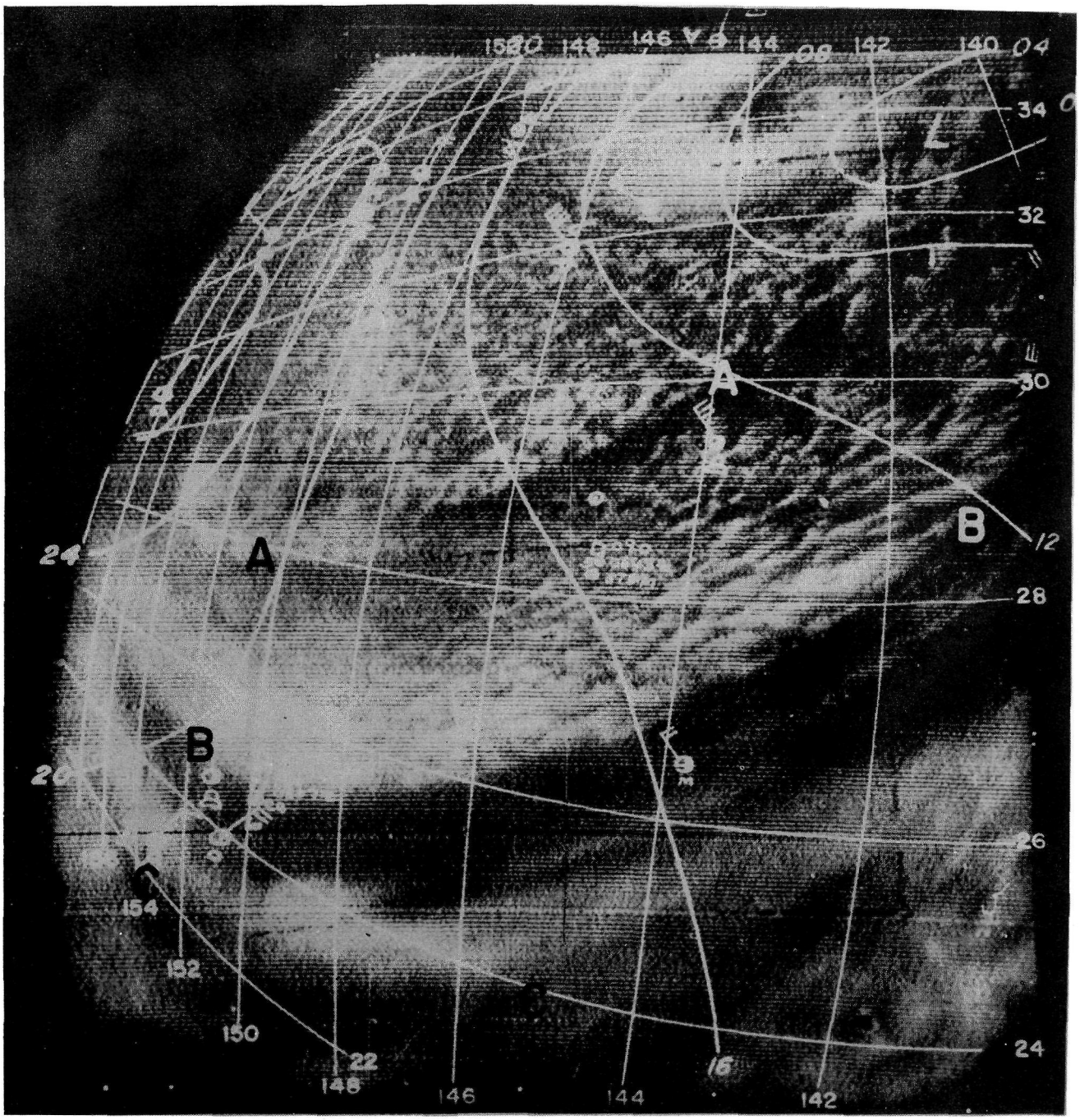
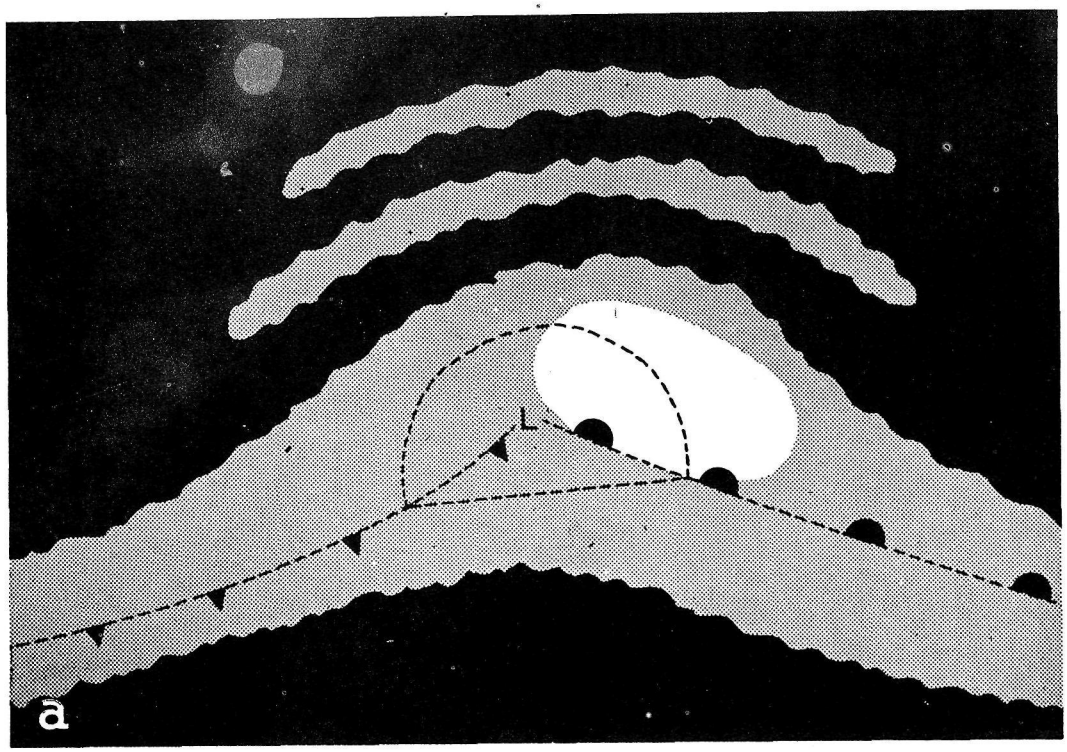


Figure 6. The cloud pattern associated with a cyclone lying between the United States and Hawaii. Latitude and longitude lines, surface isobars, and weather reports have been superimposed. April 4, 1960; 2240 GMT. (After Winston, 1960).



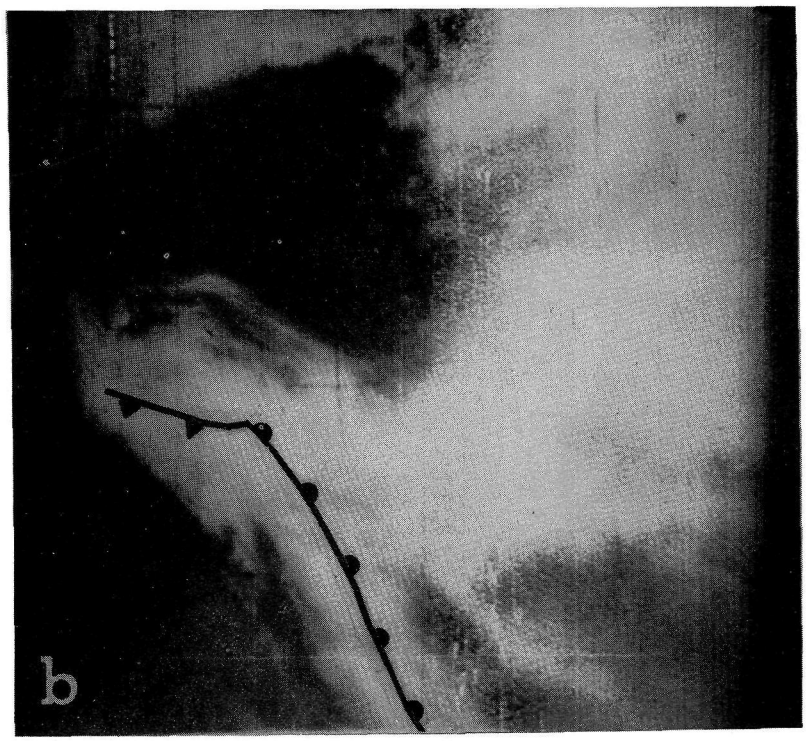
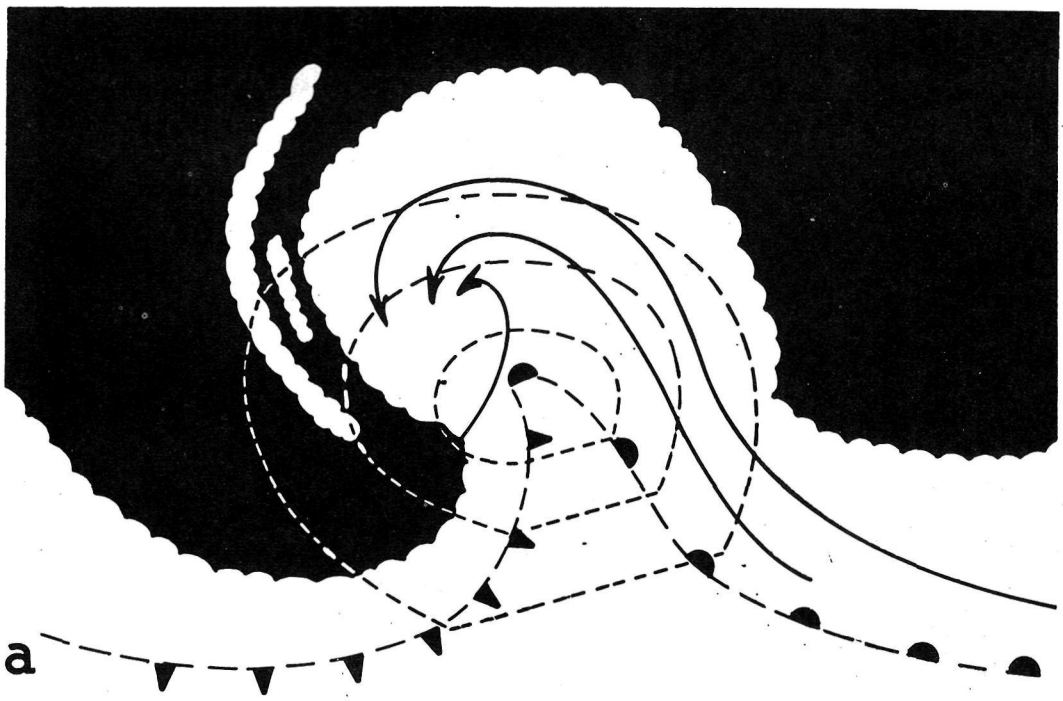


Figure 7. (a) Model cloud pattern of frontal wave as deduced from TIROS photos (Black areas are cloudless.) (b) TIROS I cloud pattern associated with frontal wave in North Pacific, May 24, 1960. (After Boucher and Newcomb, 1960)



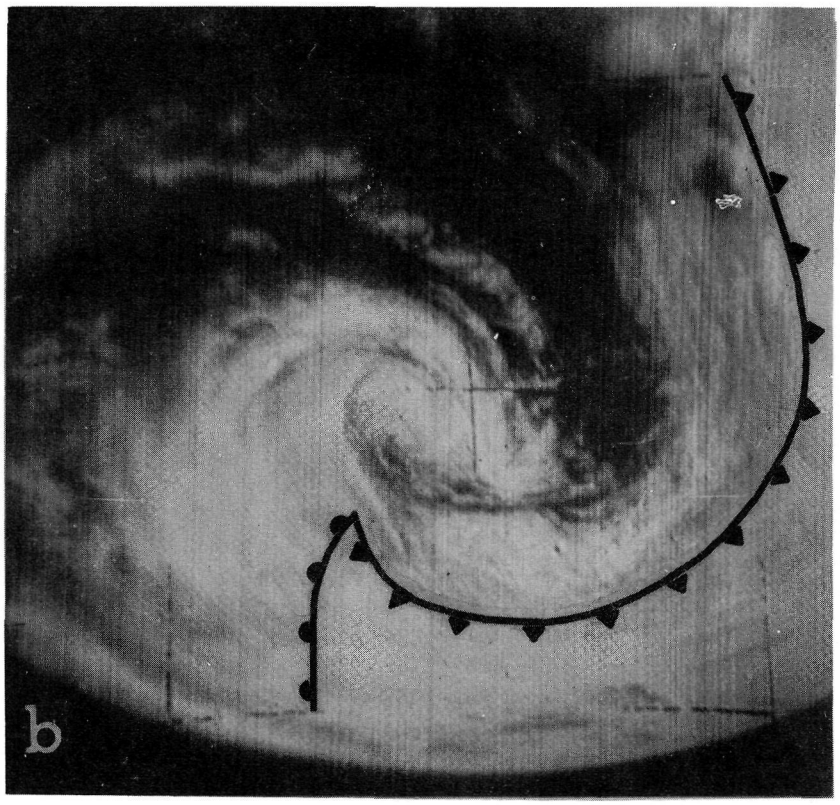
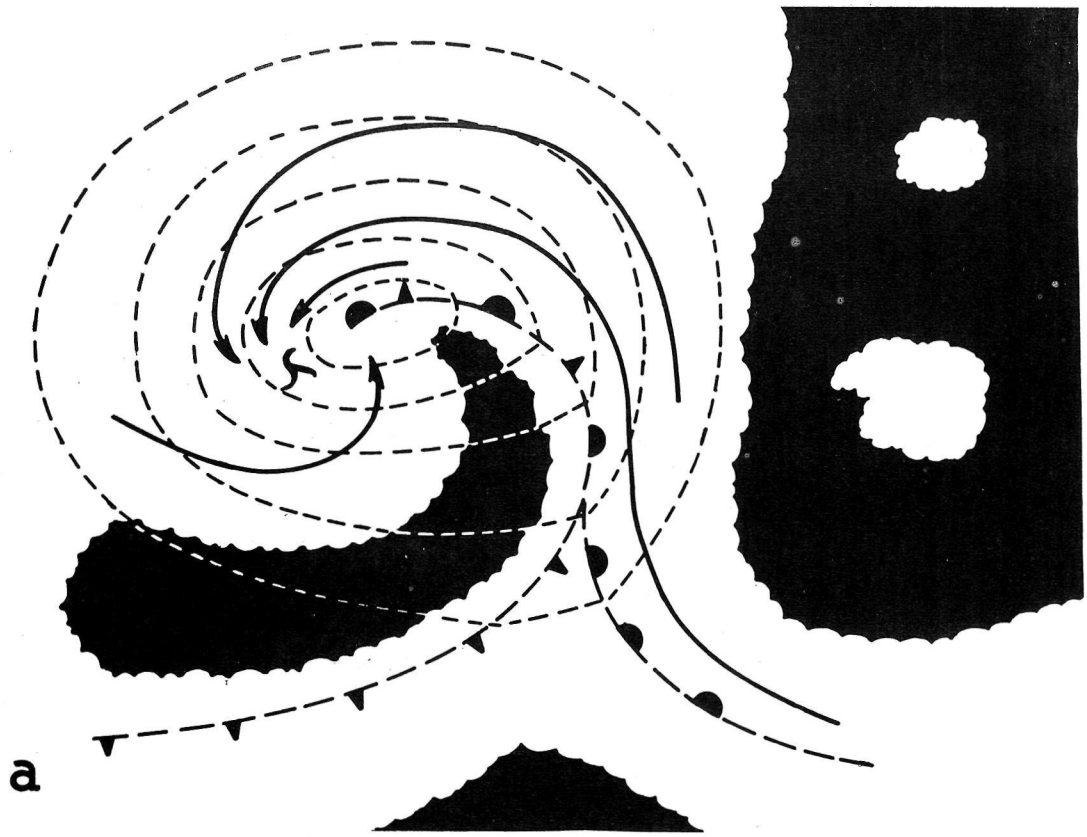


Figure 8. (a) Model cloud pattern of beginning of occlusion process. (b) TIROS I cloud pattern believed associated with start of occlusion of frontal wave, South Atlantic, April 30, 1960. (After Boucher and Newcomb, 1960)



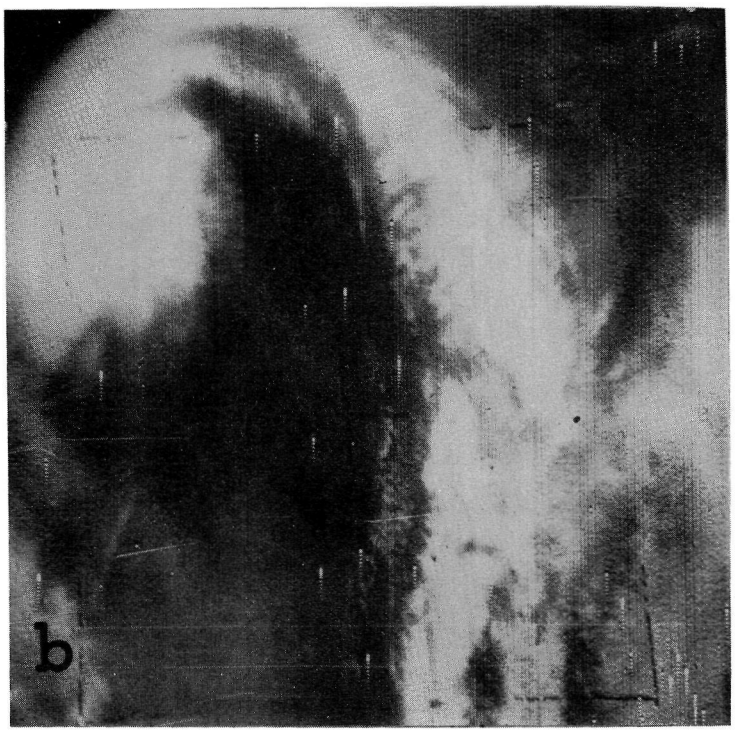


Figure 9. (a) Model cloud pattern of occluding cyclone as deduced from TIROS photos. (b) Cyclonic vortex and frontal band associated with intense occluding cyclone in Central U. S., April 1, 1960. (After Boucher and Newcomb, 1960)

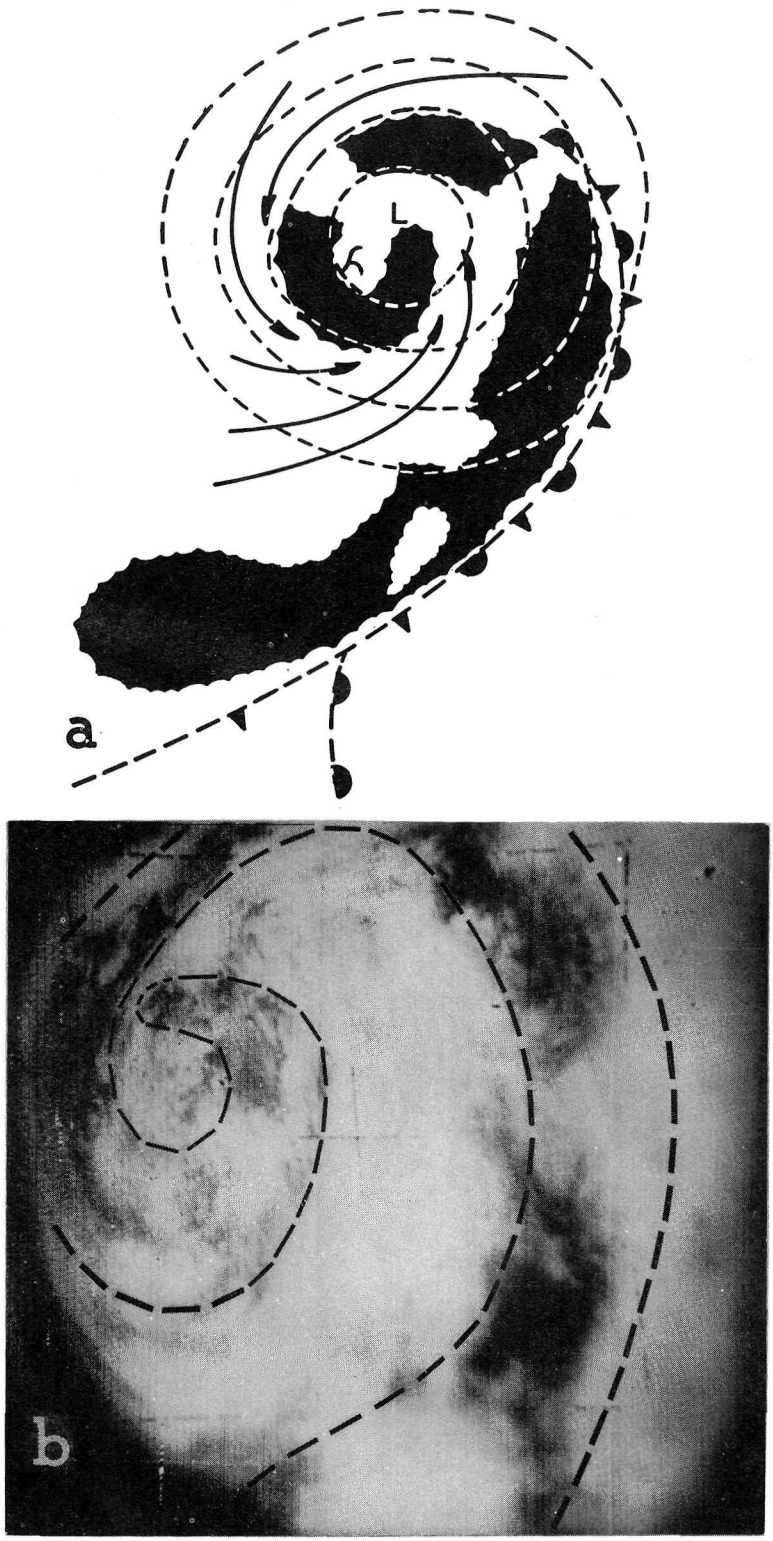
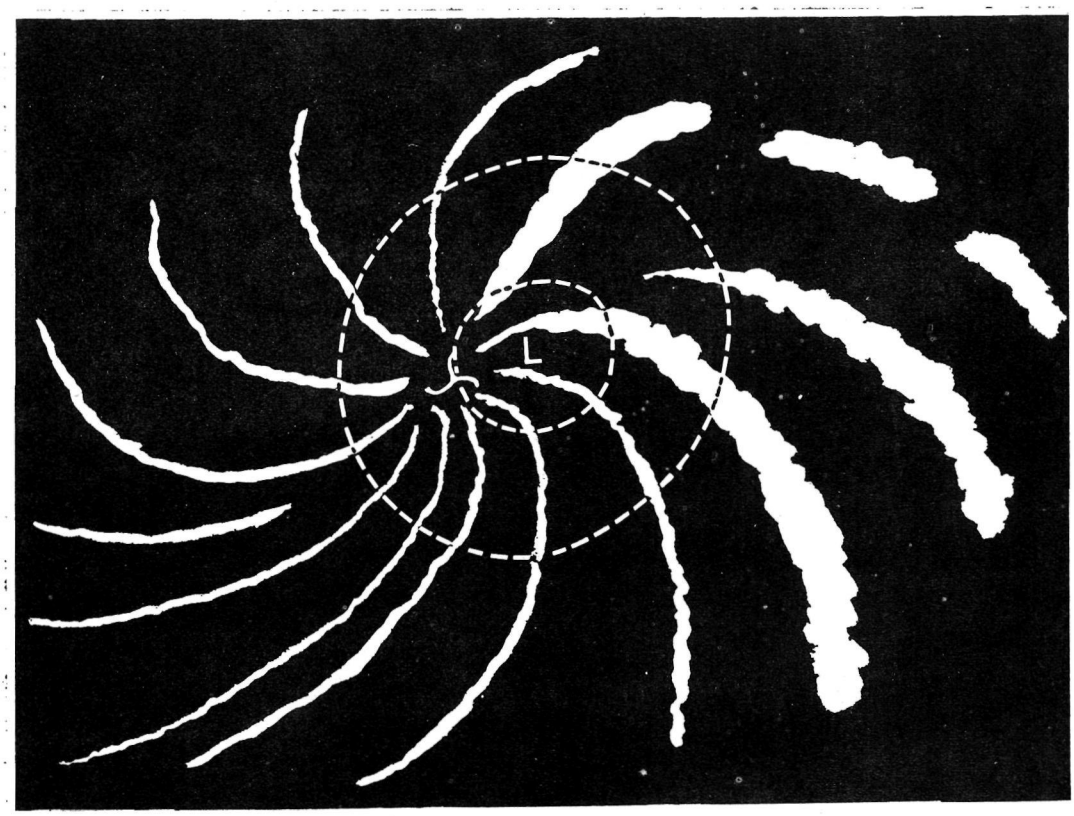


Figure 10. (a) Model cloud pattern of fully occluded, mature cyclone, as deduced from TIROS photos. (b) TIROS I vortex pattern of a decaying cyclone in the Great Lakes, May 22, 1960. Spiral "clear" zone has been outlined for identification. (After Boucher and Newcomb, 1960)



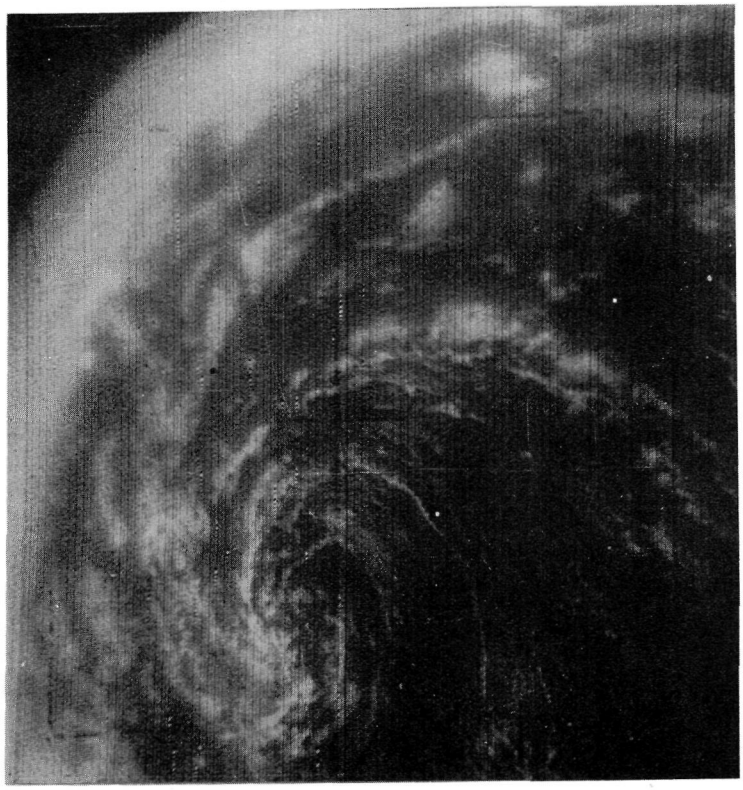
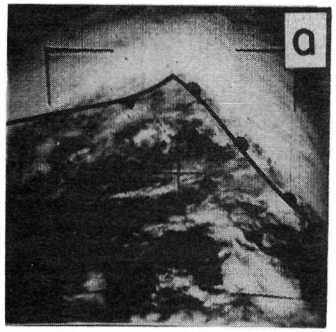
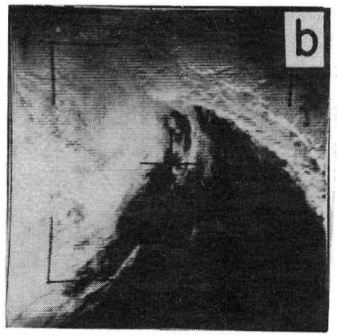


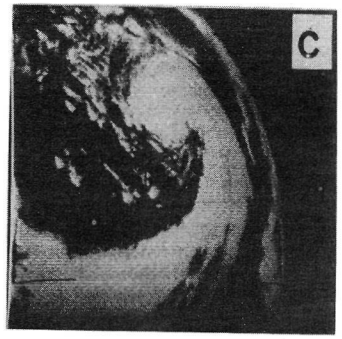
Figure 11. (a) Model cloud pattern of a dying, frontless cyclone as deduced from TIROS photos. (b) TIROS I cloud pattern associated with the final stage of a dying cyclone in the eastern Atlantic, May 9, 1960. (After Boucher and Newcomb, 1960)



TIROS IV, 807/806, fr 18
1619 GMT, APRIL 5, 1962



TIROS IV, 880-direct, fr 26
2012 GMT, APRIL 10, 1962



TIROS III, 778/777, fr 16
1357 GMT, SEPT 4, 1961

TIROS III, 679/678, fr 12
1625 GMT, AUG 28, 1961

TIROS III, 793/792, fr 15
1506 GMT, SEPT 5, 1961

TIROS IV, 1005/1004, fr 8
1123 GMT, APRIL 19, 1962

a Open wave, (52° N, 37° W, 1004 mb), April 5, 1962

b Wave cyclone beginning to occlude, (46° N, 59° W, 996 mb), April 10, 1962

c Cyclone 12-18 hours after occlusion began, (48° N, 45° W, 1006 mb), September 4, 1961

d Deep occluded cyclone near maximum intensity, (30-36 hours after occlusion began, 51° N, 24° W, 978 mb), August 28, 1961

e Weakening occluded cyclone, 36-48 hours after occlusion began, (50° N, 45° W, 1006 mb), September 5, 1961

f Dissipating cyclone, more than 48 hours after occlusion began (49° N, 4° W, 1009 mb), April 19, 1962

STAGES IN THE LIFE CYCLE OF NORTH ATLANTIC CYCLONES

Figure 12. TIROS photographs selected to show cloud patterns with various stages of cyclone development. (After National Weather Satellite Center)

Figure 7 shows the early stage of wave development. It is characterized by a localized broadening of the frontal cloud band. At times there are associated fibrous appearing semidetached bands of clouds on the cold air side.

A model of a later stage of wave development is shown in Figure 8. The wave is still open and has not yet reached the occluding stage. It is characterized by a marked northward expansion of the cloud mass associated with the cyclone and the first appearance of the vortex-like or spiral structure in the cloud mass. This spiral structure is usually clearly shown by alternate bright and dark bands as one proceeds in toward or out from the center of the cloud mass.

Figure 9 shows the occluding stage of the wave cyclone. The vortex character of the cloud mass is clearly evident but differs from the previous stage in the fact that now there is a well-marked and rather broad zone of cloudless or nearly cloudless area spiraling in toward the center.

A model of a fully occluded cyclone is shown in Figure 10. A distinguishing feature in this stage is that the cloudless or nearly cloudless band spirals completely inward toward the center of the cyclone.

Figure 11 shows the decaying stage. The spiral organization of the cloud pattern is retained, but the bands become narrower and the amount of cloudiness is diminished as compared with the cloud-free area.

A similar set of models is shown in Figure 12.

D. Tropical Storms and Hurricanes.

The character of the cloud vortices associated with tropical storms and hurricanes has much in common with that of mid-latitude cyclones. The inward spiraling bands are sometimes sharply defined and at other times not. They are sometimes many, and at other times few.

Any sizeable area of solid bright clouds in the tropics should be regarded as a potential storm. It has been found, however, that of the many such areas which have been observed in TIROS photographs, only a few have developed into significant storms.

Fritz (1962) presents a series of TIROS pictures of several stages of development of Hurricane Anna. The arrows in Figure 13 point to a bright, significantly large, amorphous cloud mass at about 10 degrees north latitude. The cloud mass is logically indicative of significant upward vertical motion, but as yet the cloud pattern gives little indication of there being a closed circulation. The arrows in Figure 14 point to the same mass of clouds nearly 24 hours later. Spiral bands have now appeared and there is substantial evidence of cyclonic circulation. The arrow in Figure 15 points to the satellite's view of the storm which by now is a full-grown hurricane.

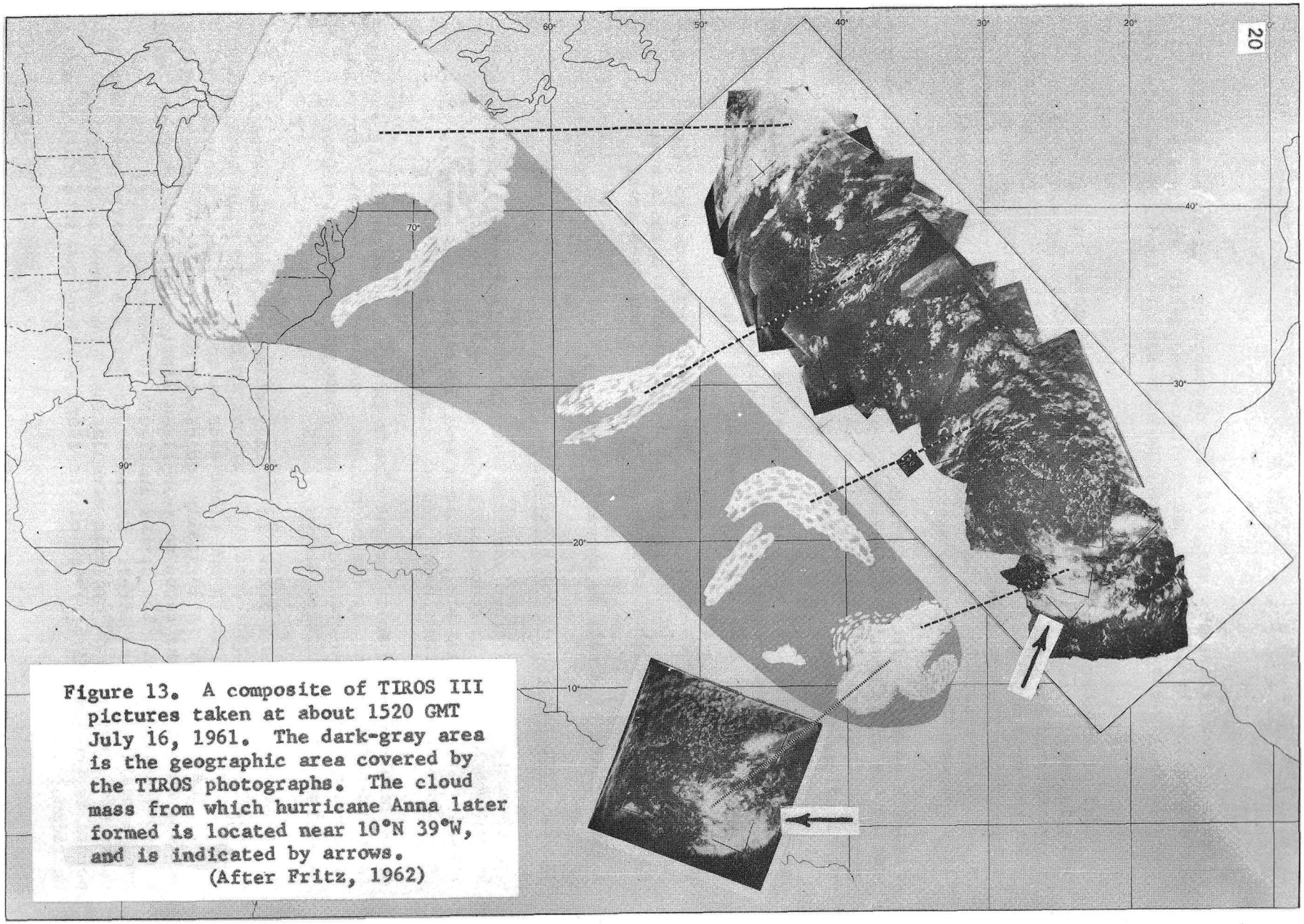


Figure 13. A composite of TIROS III pictures taken at about 1520 GMT July 16, 1961. The dark-gray area is the geographic area covered by the TIROS photographs. The cloud mass from which hurricane Anna later formed is located near 10°N 39°W, and is indicated by arrows.
(After Fritz, 1962)

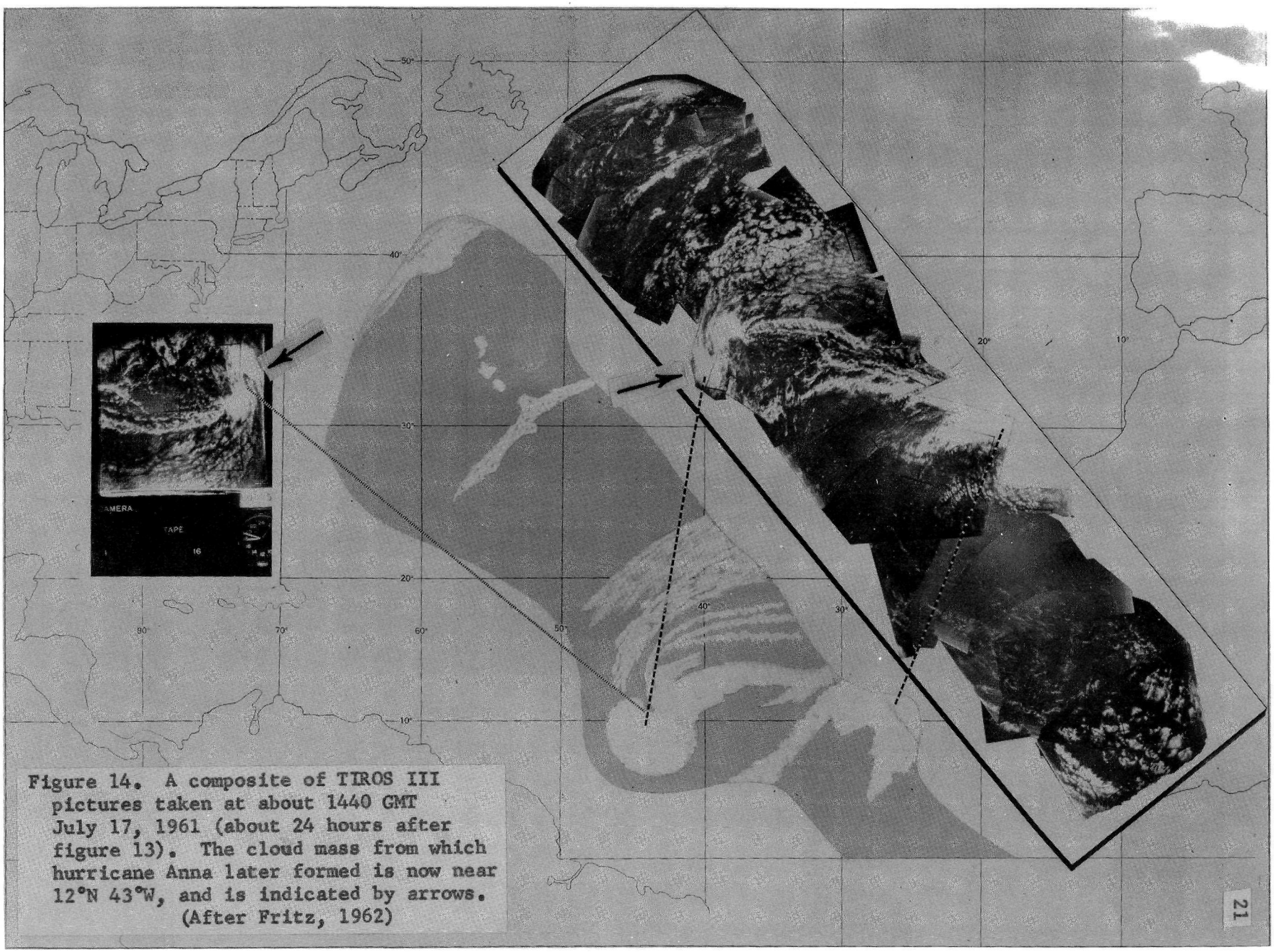


Figure 14. A composite of TIROS III pictures taken at about 1440 GMT July 17, 1961 (about 24 hours after figure 13). The cloud mass from which hurricane Anna later formed is now near 12°N 43°W, and is indicated by arrows. (After Fritz, 1962)

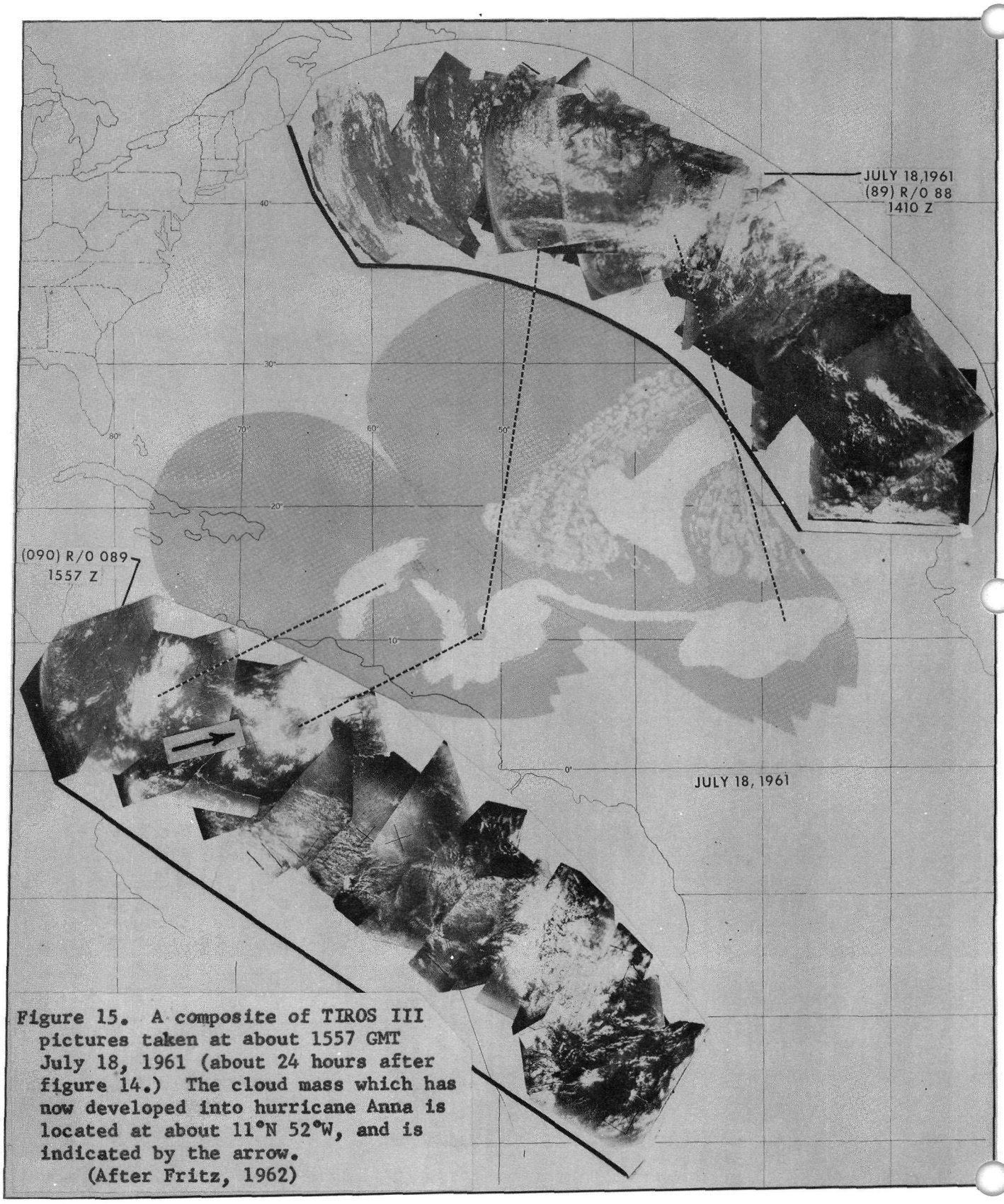


Figure 15. A composite of TIROS III pictures taken at about 1557 GMT July 18, 1961 (about 24 hours after figure 14.) The cloud mass which has now developed into hurricane Anna is located at about 11°N 52°W, and is indicated by the arrow.
(After Fritz, 1962)

There are some indications that in the early stages of tropical storm development, the alternate clear and cloud bands are rather broad, not unlike the pattern associated with the mature stage of extratropical storms. As the tropical storm develops further, however, the clouds appear to consolidate, with the only distinctly clear bands being rather narrow and located toward the periphery of the storm. Sometimes the hurricane "eye" is visible and sometimes not.

Fett (1963) has suggested the possibility of detection of the high level anticyclone surmounting developing hurricanes through cirrus streamers sometimes visible in cloud photographs.

E. Winds.

Miller (1963) has demonstrated the use of operational nephanalyses in determining broadscale 500-mb (mid-tropospheric) flow patterns in sparse data regions. His technique is based on the observation made early in the TIROS program, that major cloud masses and at times even smaller details of cloud structure tend to be elongated along the direction of mid-tropospheric flow. Furthermore, in the region of the mid-latitude westerlies, the major cloud masses are most often found near or slightly downstream from troughs. Clear areas, or those showing only small cumulus clouds, are most often found where the mid-tropospheric flow is anticyclonic. Miller combines these assumptions with a judicious use of climatology and synoptic models to derive estimates of the 500-mb flow patterns. For details, the reader is referred to Miller's original article.

Figure 16 shows bands or lines of clouds which ground observers report as being cirrus and middle clouds. It can be seen especially over eastern and southern Washington that this northeast/southwest streakiness is quite uniform and parallel with the mid-tropospheric flow.

Organization of clouds into bands on a somewhat larger scale is shown in Figure 17. This example, from the North Pacific, shows rather clear cut broadscale banding aligned nearly with the mid-tropospheric flow.

At times, the low level flow can be deduced from satellite photographs. This is done with most confidence in the case of cumulus streets, of the kind described by Kuettner (1959). An example of these is shown in Figure 18. While this example is taken from the tropics, the streets occur in extratropical regions as well.

In the above suggestions, there is a 180° ambiguity involved. This can usually be resolved on the basis of climatology or continuity. At times, however, one can recognize situations in which cirrus streamers are being blown off the tops of thunderstorms. In these cases, the wind direction at the cirrus level can usually be inferred without the ambiguity. An example of this is shown in Figure 19. Thunderstorms can be seen over the Sierras of California with cirrus streamers being blown off to the northeast.

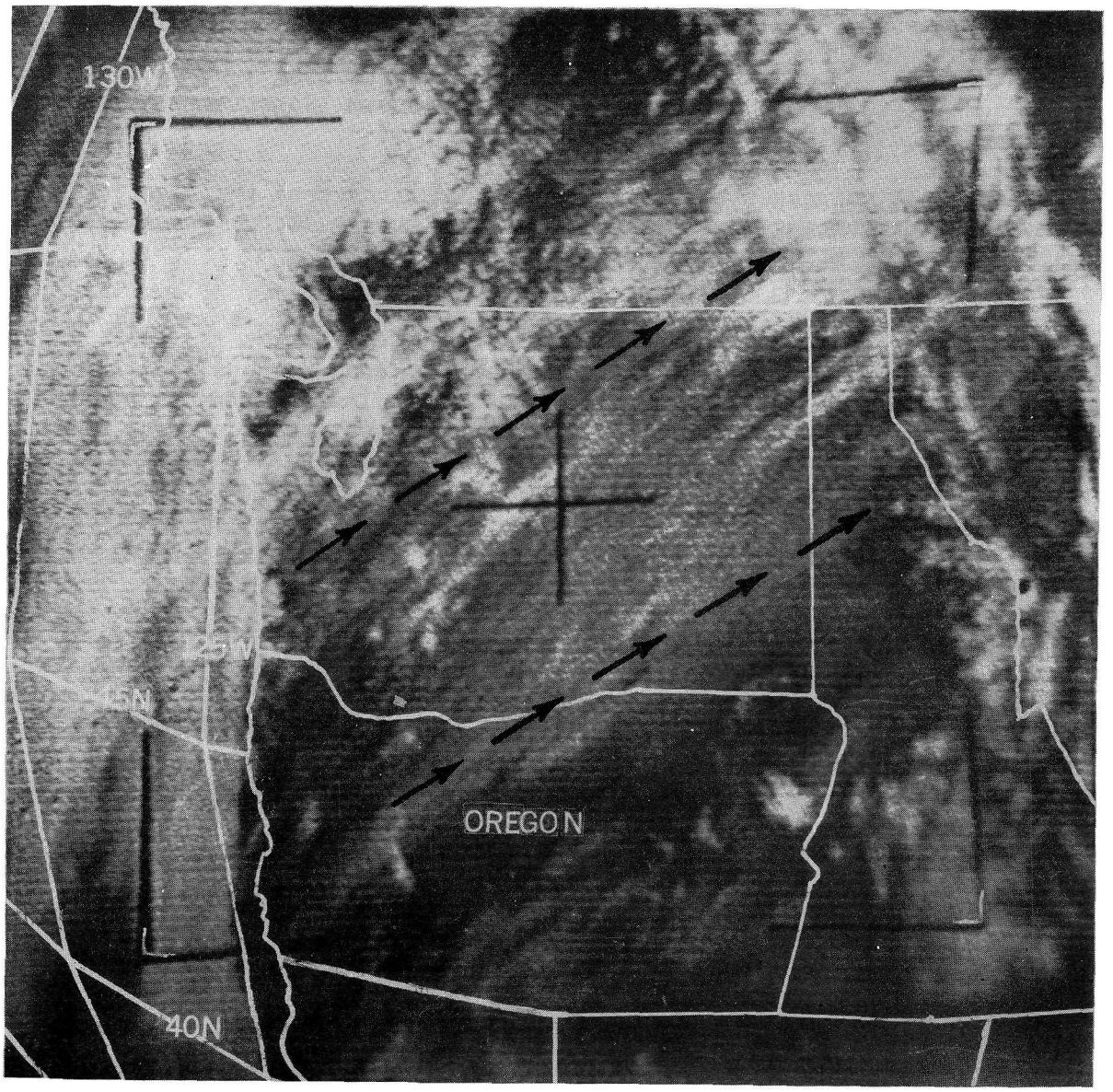


Figure 16. TIROS IV view of clouds over the Pacific Northwest on April 23, 1962. Superimposed are streamlines of the mean flow between 500 and 300 mbs.

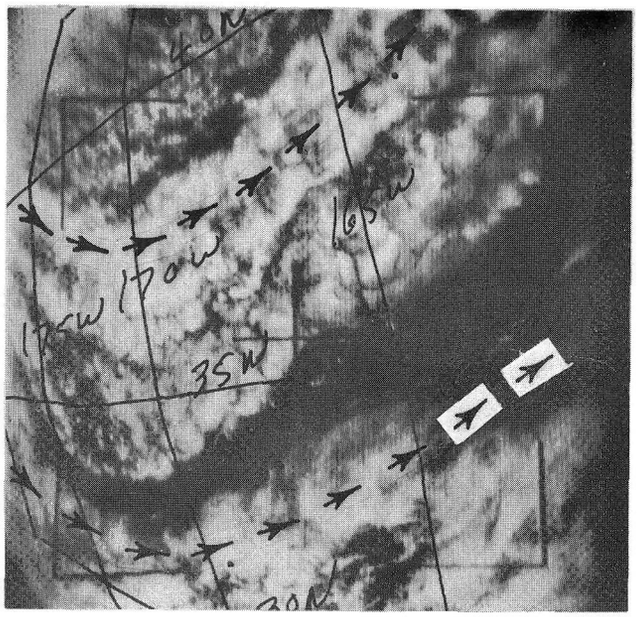


Figure 17. TIROS VII view of large scale bands of clouds in the North Pacific on August 22, 1963. The mid-tropospheric streamlines are superimposed.

Figure 18. TIROS view of Middle East. Note that the cloud lines or streets over the water are aligned parallel with the superimposed low-level streamlines. (After Conover, 1963)

Figure 19. TIROS V view of California on June 22, 1962. Note the thunderstorms over the Sierras with cirrus streamers being blown in the general direction of the 200 mb winds. (After Conover, 1963)

Another example of situations where the ambiguity is not present is that of wave clouds in mountain areas. Figure 20 shows an example of wave clouds formed downstream from the Appalachian Mountains. In typical fashion, the clouds formed in the crest of the waves are rather closely and evenly spaced. They are oriented nearly parallel to the mountain range and perpendicular to the flow. The features that distinguish these formations from those in which cloud lines lie along the flow are the presence of the mountain range and the uniform spacing of the cloud lines.

Theoretical and experimental work by Corby (1957) and others have shown that conditions favorable for the formation of mountain waves are: the presence of a stable layer in the air mass; wind blowing at nearly right angles to the mountain barrier; and some increase in wind speed with height but little change in wind direction with height through a substantial layer above the tops of the mountain range. Furthermore, Corby has presented observational evidence of the relationship between the wave length of mountain waves and a mean layer wind speed. He determined the wave length from vertical velocities deduced from radiosonde ascent rates and from radar observations. Fritz (personal communication) has more recently added the more direct evidence of measurements of wave lengths from satellite photographs. The evidence added by Fritz has supported Corby's conclusions. A composite diagram is shown in Figure 21.

The practical implication, from our point of view, is that on observing mountain wave clouds on satellite photographs, one can assume that the wind near the level of the tops of the mountain range is blowing nearly perpendicular to the range. Furthermore, there is probably some increase in wind speed with height, but little change in wind direction with height. By measuring the spacing between the lines of mountain wave clouds (wave length), one can derive a first approximation to the mean wind speed between 850 mb. and 200 mb. from Figure 21.

F. Jet Streams.

Conover (1959) and Kadlec (1963) have presented models in which under many conditions the jet stream marks the northern (cold side) boundary of a cloud shield. This shield is usually made up of cirrus clouds but sometimes of altostratus. The implication is that where a satellite photograph shows such a boundary of a cloud system, the existence of a jet stream at this boundary should be suspected. An example of this is shown in Figure 22. The jet stream corresponds quite closely with the northern boundary of a well defined band of clouds lying across Florida. A cold front marks the southeastern edge of the clouds. There are multilayers of clouds with showers near the cold front. On the jet stream side of the band the clouds are reported as being altocumulus and cirrus. It is possible that some cirrus, not visible in the photograph, extends to the north of the jet stream. It is often the case that cirrus is not detectable in TIROS photographs, especially if the cirrus occurs in scattered elements or if it is very thin even though it might be overcast.

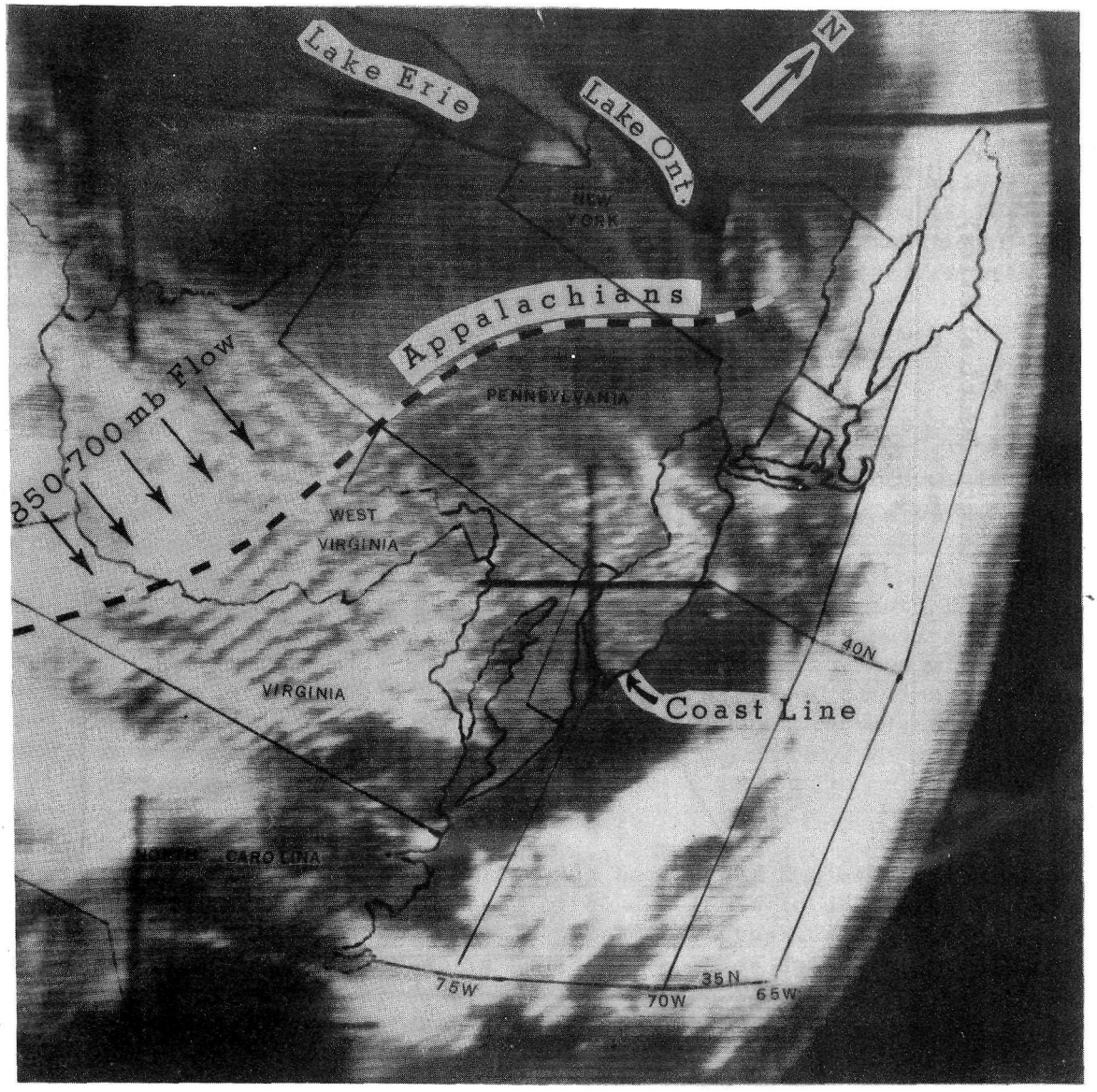


Figure 20. TIROS V view of wave clouds to the lee of the Appalachians. Photo taken April 18, 1963.

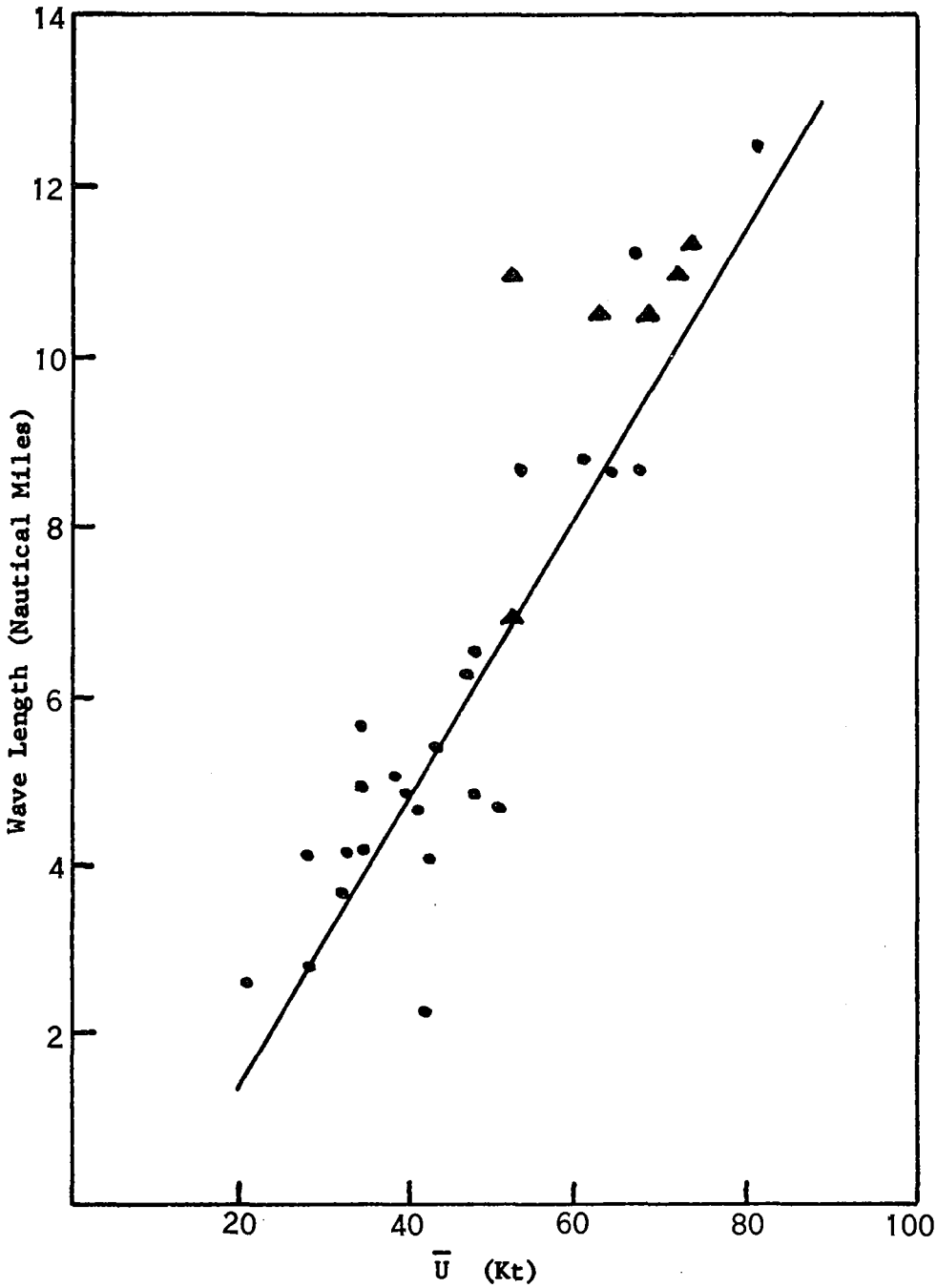


Figure 21. Diagram showing relationship between mean layer wind speed and wave length of mountain waves. Dots (.) represent cases taken from Corby (1957) in which wave length was determined by indirect methods and mean wind speed ($\bar{U}$) is taken through an appropriate layer. Triangles (▲) represent cases added by Fritz, in which the wave length was determined from satellite photographs and the mean wind speed is that from 850 mb to 200 mb. (Modified from diagram presented by S.Fritz at IUGG Meeting in Berkeley, California, August 1963.)

Figure 22. TIROS V view of band of clouds across Florida. Superimposed are the surface cold front and the 200 mb jet stream. March 6, 1963.

Several principles are illustrated in this figure. It will be noted that the jet stream is blowing generally parallel to the front. This being the case, the presence of post cold front cloudiness rather than no cloudiness or prefrontal cloudiness is to be expected. Furthermore, it is to be expected that the jet stream coincides generally with the northern boundary of the post cold front cloud mass.

The practical application of these principles is as follows: where a frontal cloud band can be established as post frontal rather than prefrontal, one could assume as a first approximation that the flow aloft is roughly parallel to the front and also that the jet stream is located near the cold-side edge of the cloud band.

A less precise, but still potentially useful relationship between clouds and the jet stream is shown in Figure 23. In a general way, the jet stream marks the northern edge of the major cloud system from Missouri eastward. Some clouds do extend north of the jet stream into West Virginia. However, while it may not show clearly in this reproduction, the character of these clouds appears somewhat different from those to the south of the jet stream. Those to the south exhibit "streakiness" which is oriented predominantly east/west. The clouds to the north tend to be streaked more north/south or not at all. This question of differences in apparent cloud texture across the jet stream is currently under investigation at the Weather Bureau's National Weather Satellite Center. The prospect of early useful results is promising.

G. Air Mass Stability.

Investigation has suggested that there are certain types of cloud patterns from which deductions of air mass static stability can be made with some confidence. There is some uncertainty in these relationships, but in the absence of other data these patterns would serve as the basis for the best available estimate of stability of the lower troposphere. Krueger and Fritz (1961) discuss cellular appearing clouds arrayed in circles or arcs surrounding clear areas. An example of these is shown in Figure 24. They exhibit something of the appearance of Bénard cells. The diameter of the circles range from on the order of 20 to 50 miles. Synoptic data studies in a number of these situations show that these patterns appear in air masses which are slightly colder than the underlying water surface. The lapse rate is nearly adiabatic through the lower layer (some 3,000 to 10,000 feet deep). This unstable layer is usually capped by a well-marked inversion. Furthermore, the wind shear through the lower unstable layer is quite small. It is suggested that these patterns are more common over ocean areas than over land. Krueger and Fritz also suggest for empirical as well as theoretical reasons that the larger the diameter of these circles, the deeper the layer of free convection, that is the higher the inversion. They suggest a rough initial estimate of the height of the inversion as being about 3% of the diameter of the circles formed by the cloud elements.

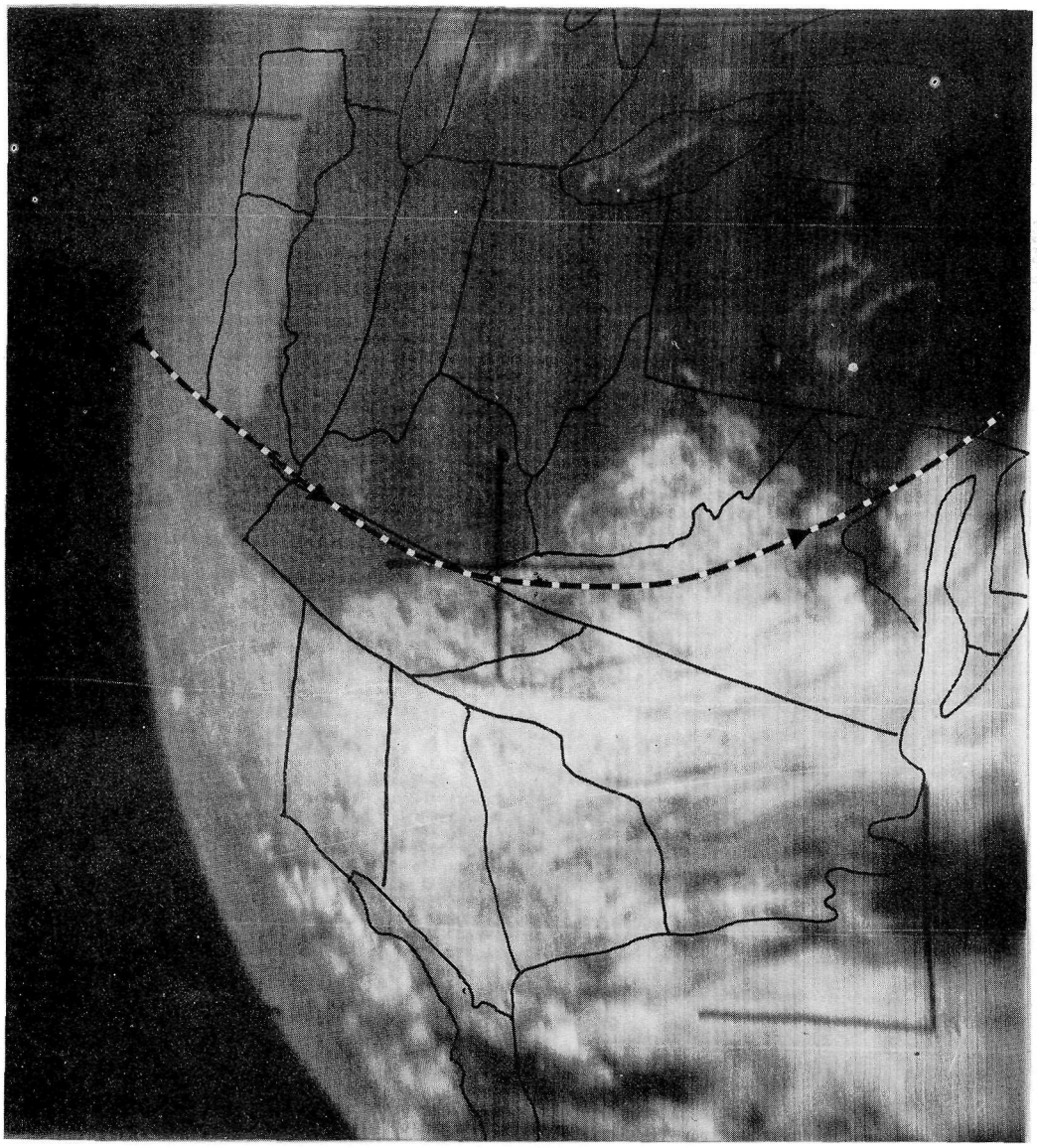


Figure 23. TIROS V view of clouds over Eastern U. S. on September 7, 1962. The jet stream is superimposed.

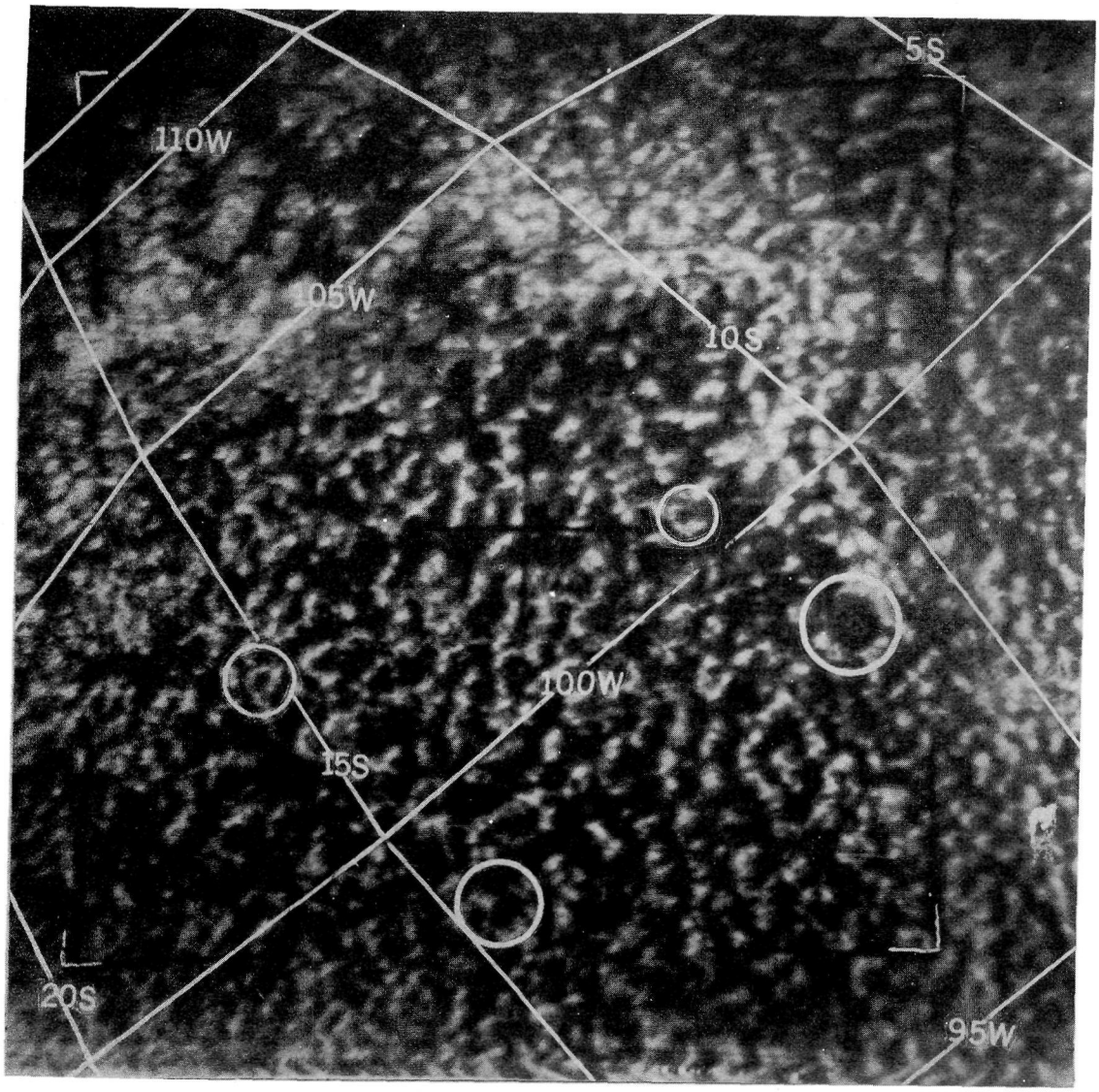


Figure 24. TIROS III view of tropical stratocumulus formations resembling Benard cells. Typical cells are outlined.

In areas where the inversion is somewhat higher, the cloud pattern is more likely to take the form of lines or streets. Such a pattern is shown in Figure 25. This photograph shows cloud lines over tropical waters. The lines are apparently made up of cumulus and towering cumulus clouds. It is probable that the clouds in different areas extend to different altitudes. If this is true, the organization reflects the winds at different altitudes in different areas rather than resembling streamlines in a horizontal layer. This is in contrast with the simpler situation which was shown in Figure 18.

Often, very cold air flowing off a land surface out over warmer water forms a unique pattern of clouds. One example is shown in Figure 26. At the time of this photograph, the arctic air mass had overspread the Eastern States and out into the Atlantic. The cold front cloud band can be seen at about 30N,70W, oriented northeast/southwest. The cloud pattern between the front and the coast suggests the following process: The cold, dry and stable air flows from land out over the warmer water. The air mass begins to pick up moisture. Through heating from below and some mechanical turbulence a shallow unstable layer appears in the lower levels. As this process continues, clouds begin to form in rather fine, closely spaced lines along the wind. As mixing takes place through a deeper and deeper layer, the cloud lines become more and more coarse and extend to higher levels.

Thunderstorm cloud masses, indicative of instability through a relatively deep layer, have a number of distinguishing characteristics. Figure 27 shows groups of thunderstorms in New Mexico and Colorado. The clouds are quite bright, often indicative of considerable vertical depth. In addition, the considerable height to which these clouds have built is suggested by the shadow cast on the east side of the groups of clouds.

Figure 28 shows a mass of midwestern U. S. storms in a situation studied by Whitney (1961). Of interest here as a possible distinguishing characteristic useful in sparse data regions is the scalloped appearance of the southern boundary of the cloud mass labeled A. Presumably each of the "mounds" represents an individual thunderstorm. Otherwise, the boundaries of individual thunderstorms are obscured by middle and high clouds. Likewise, whatever scalloped shape may exist on the northern boundary of the entire mass is also obscured by middle and high clouds.

H. Snow Fields.

A problem of interpretation of clouds in satellite photographs sometimes arises from the fact that there is little difference in reflectivity between some cloud masses and snow fields. It is obvious that this becomes a problem primarily in the cold season and over land areas. In this respect it is fortunate that the largest volume of conventional data is available over land areas.

There are several techniques which, when used together, can usually go a long way toward distinguishing between clouds and snow.

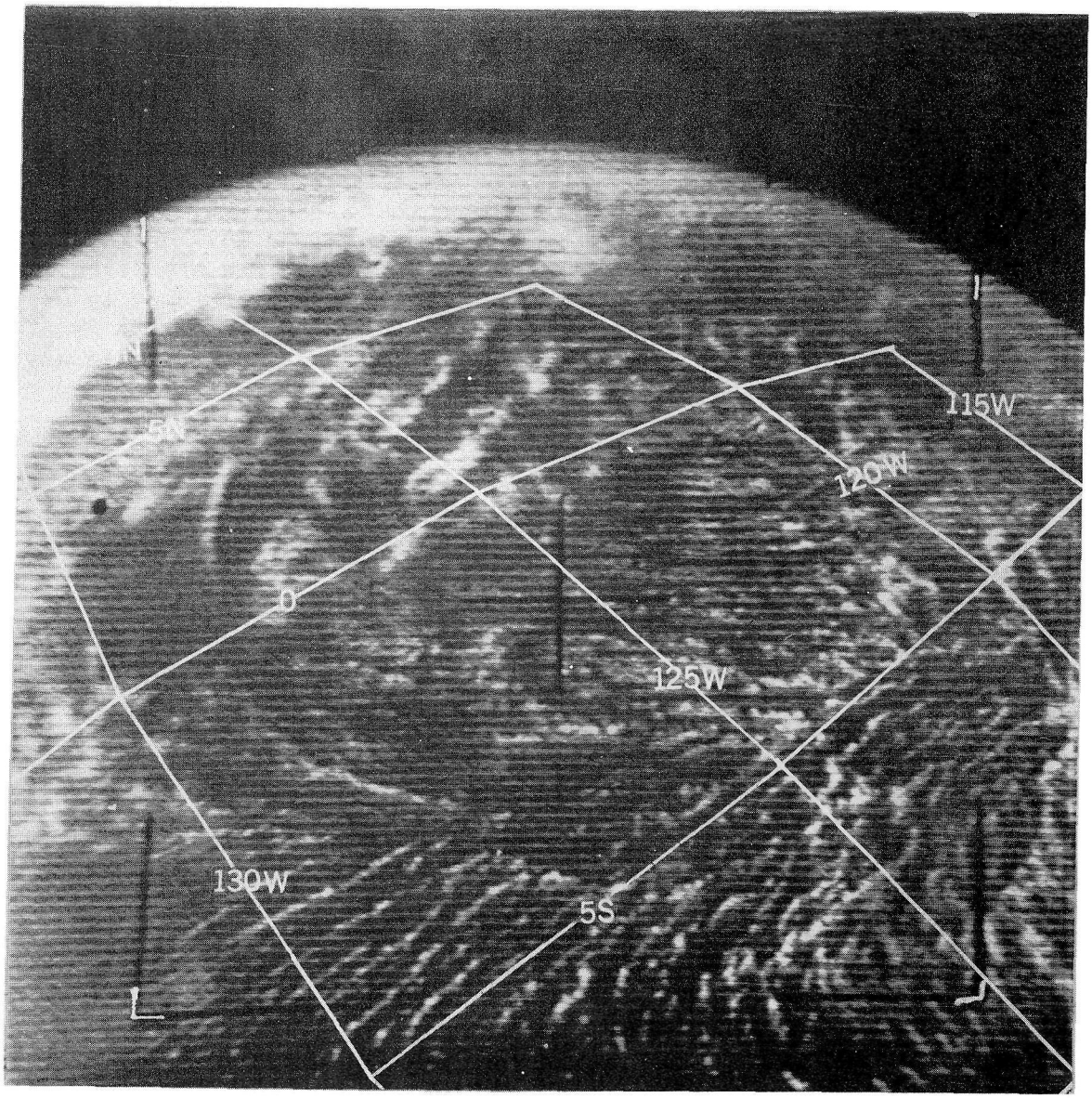


Figure 25. TIROS IV view of bands of cumulus and towering cumulus clouds over tropical waters.

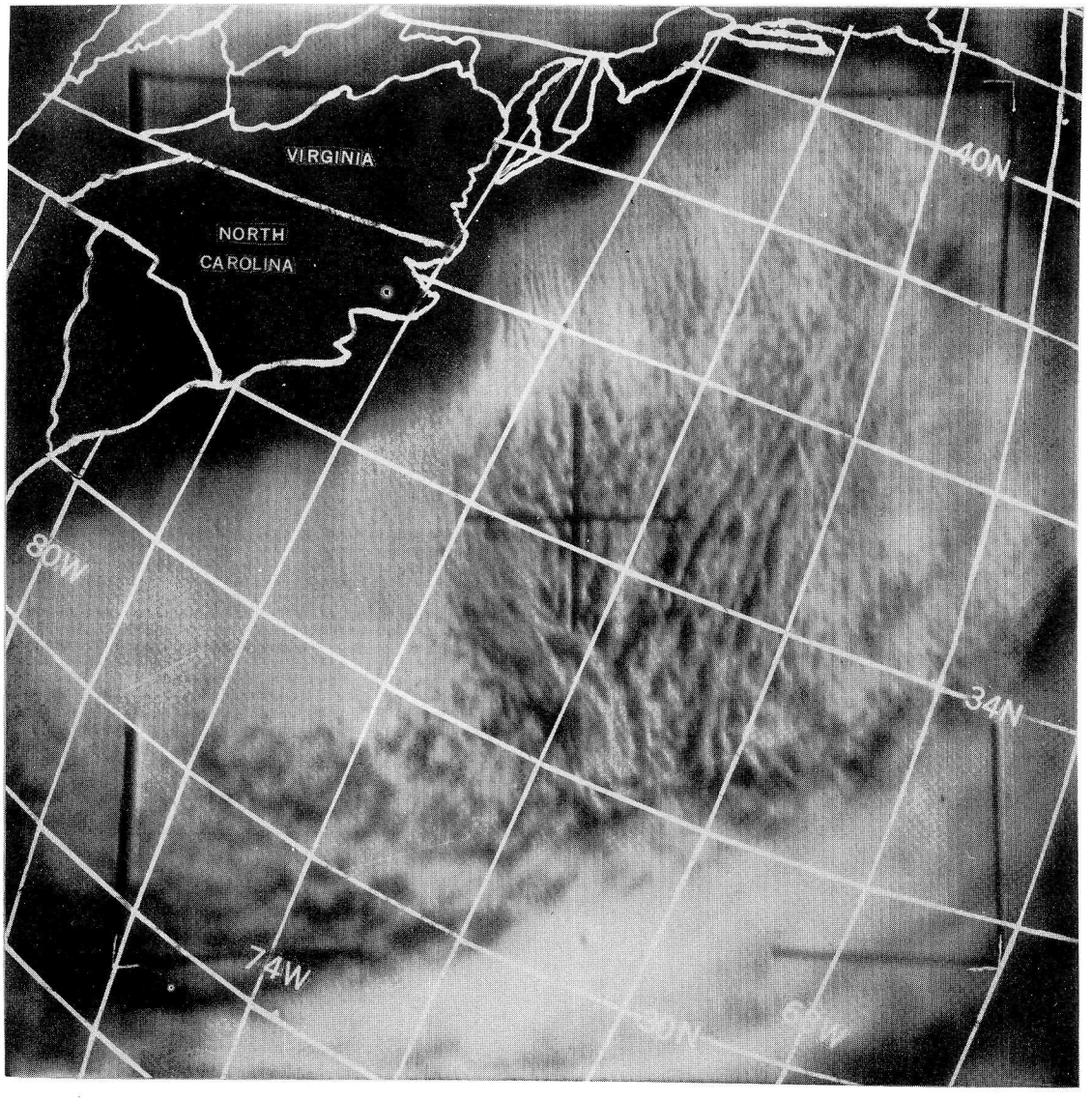


Figure 26. Clouds formed as arctic air flows out over Atlantic waters off Eastern U. S. TIROS V, December 13, 1962.

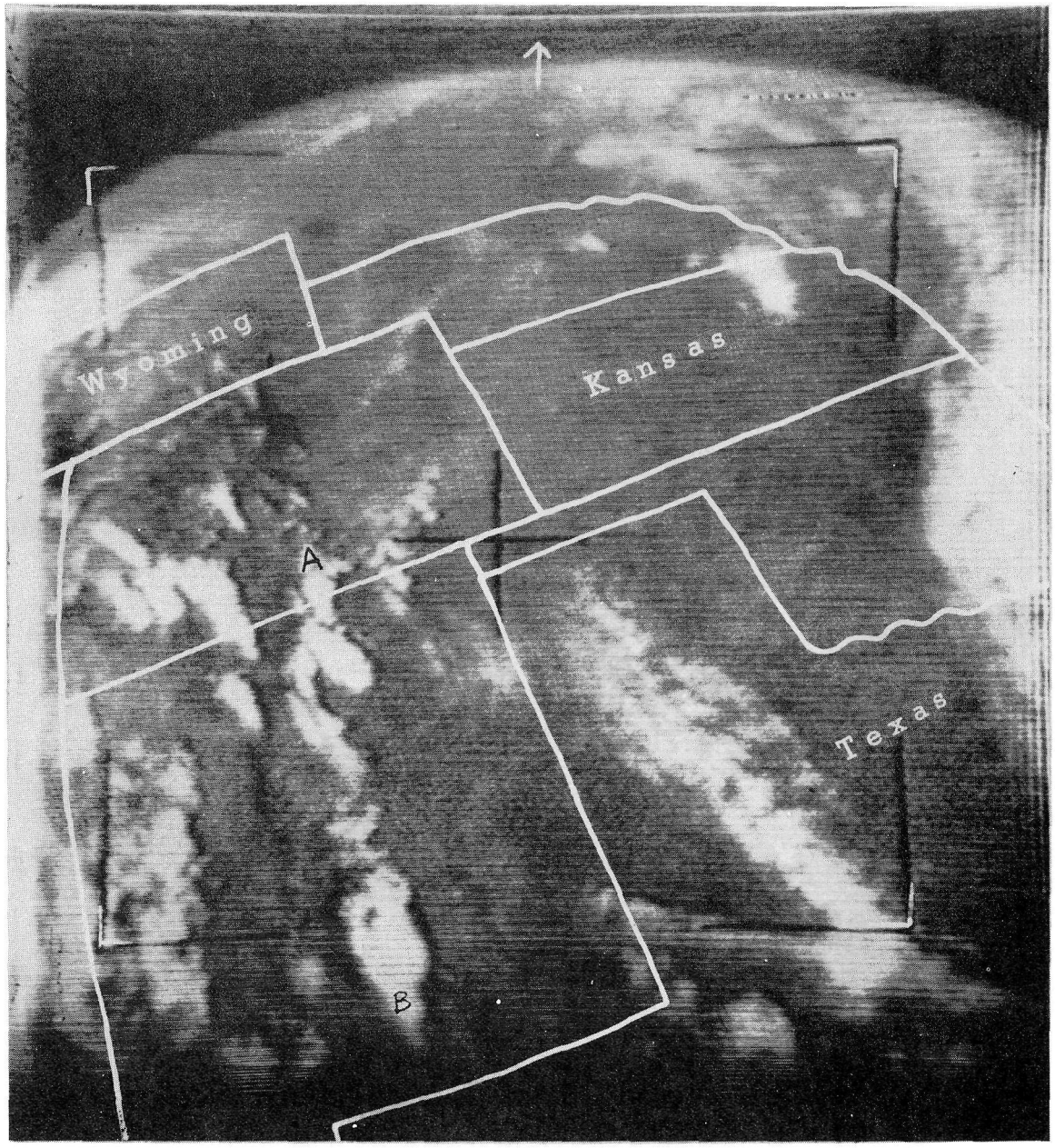


Figure 27. TIROS view of thunderstorms in New Mexico and Colorado. Note shadows to the east of the thunderstorms.

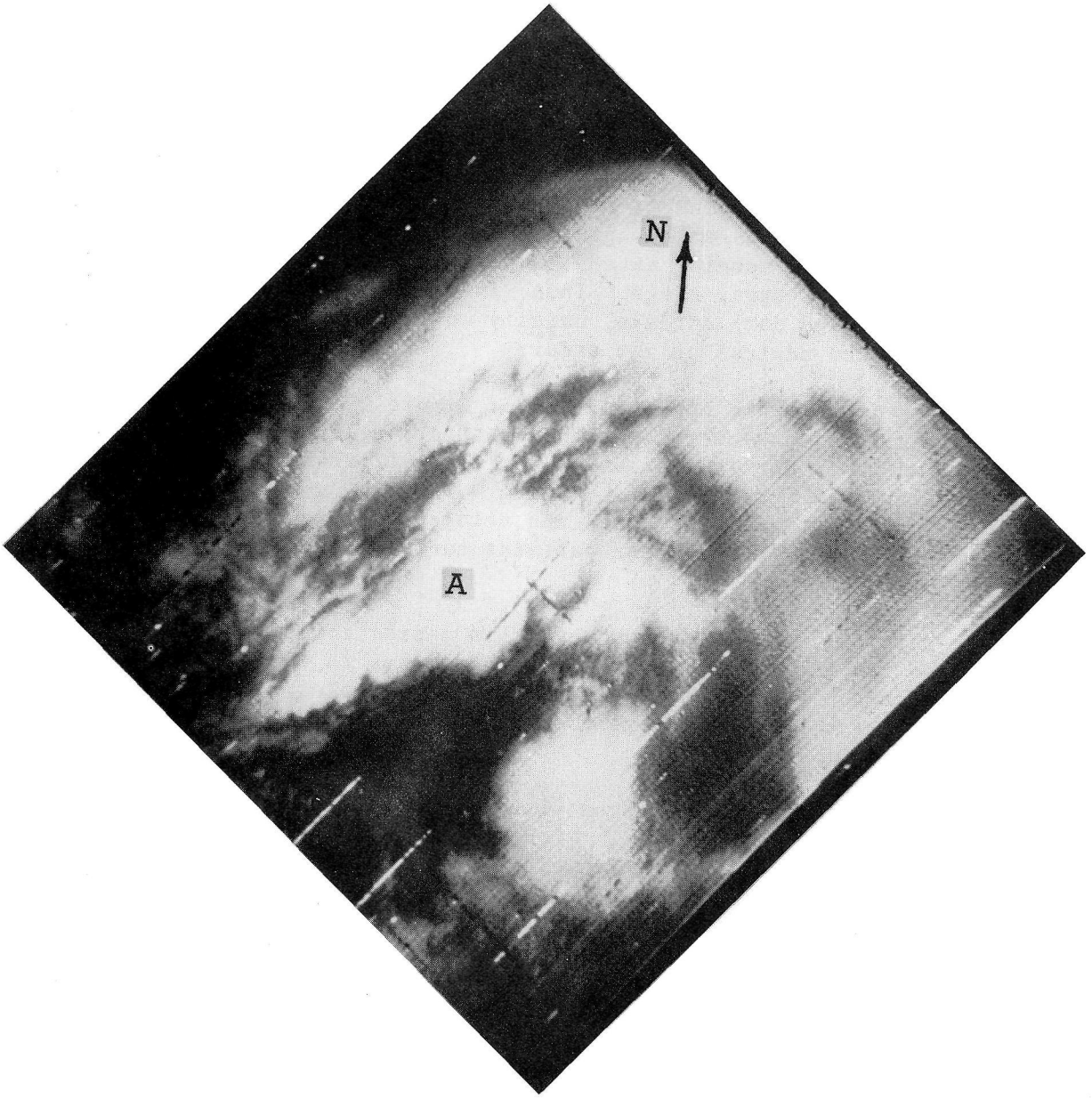


Figure 28. TIROS I photograph showing thunderstorm masses over the midwestern U. S. on May 16, 1960. Note especially the scalloped shape of the lower (southern) boundary of the cloud mass labelled A.

1. Characteristic patterns.

Narrow angle (telephoto) TIROS photographs have revealed characteristic patterns that indicate snow over mountainous areas. These show as characteristic patterns particularly because of the fact that the mountain ridges tend to be snow covered, while the valleys tend to be relatively snow free. Therefore, the central ridge of the mountain range will usually show as an elongated bright area. Alternate ridges and valleys usually extend outward and at roughly right angles from the central ridge. Thus, in the usual situation alternate bright and dark streaks, usually well-defined, emanate outward from the central bright area.

The area in the upper portion of Figure 29 shows the characteristic snow-over-mountains pattern, while that in the central and lower portions shows an entirely different pattern. The latter is more amorphous and represents clouds. Improvements in the later TIROS camera and related systems are such that at the present time, these patterns can be recognized on the wide angle photos.

Tarble (1962) has shown that this characteristic snow pattern is revealed over major mountain systems in the wide angle photos. Figure 30 is taken from his examples. The characteristic pattern is again quite obvious and similar to that shown in Figure 29.

2. Stability of patterns with time.

Recognizing the fact that cloud patterns are likely to change in some degree with time, those patterns in which there is no detectable change with time should be suspected as being snow rather than clouds. Within the limits of the resolution of the system, comparing the view from adjacent orbits (some 100 minutes apart) may not be a reliable indication of the stability of the pattern for these purposes. On the other hand, comparing the views 24 hours or even several days apart should be extremely reliable.

3. Other data.

There are times, especially over the Great Plains, when the satellite photographs show considerable expanses of rather uniform bright area. A study of the reported snow depths at the synoptic reporting stations and the reports of clouds as shown on the Weather Depiction Chart will usually reveal whether the general area is one of snow, clouds or both.

The general problem of detection of ice in northern oceans and inland waters is similar to detecting snow fields. The ice

Figure 29. Narrow angle TIROS photograph of snow and clouds. The dendritic pattern in the upper portion of the photo is snow over mountains. The more amorphous pattern in the lower portion is clouds.

TIROS IV

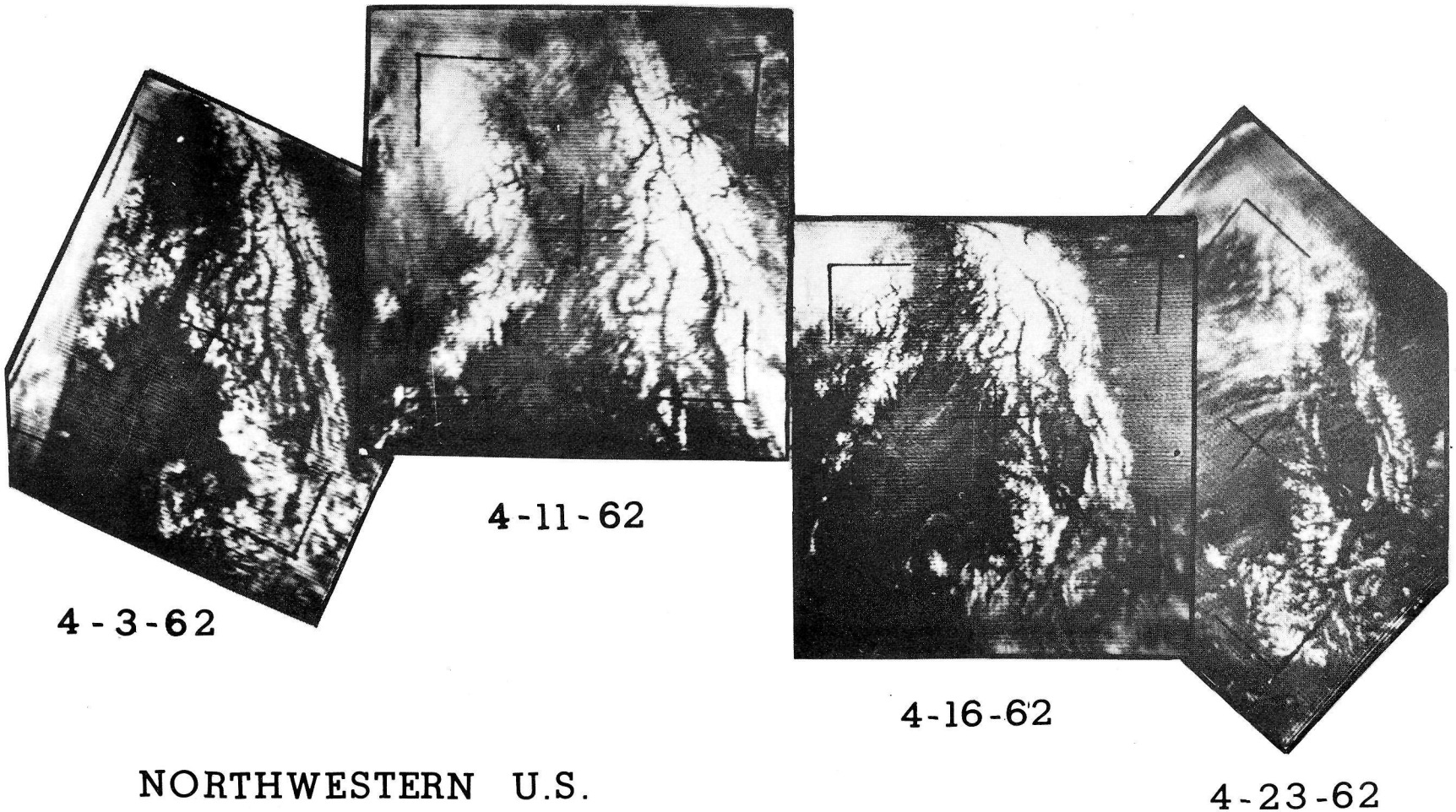


Figure 30. Satellite views of snow over mountains. (After Tarble, 1962)

appears white, does not change much from day to day, and has sharply defined edges and lines indicating breaks and leads.

IV. SUBSYNOPTIC SCALE USES OF SATELLITE CLOUD DATA

This section is primarily concerned with the problem of relatively short-period forecasts of cloud and related phenomena. So far as the Weather Bureau is concerned the magnitude of this problem is significantly greater over continental areas than over water areas. Therefore, the emphasis here will be on the use of satellite cloud data in giving additional detail of cloud distribution beyond that available from conventional reports such as available over the 48 contiguous United States.

A. Thunderstorms and Squall Lines.

Satellite photographs of thunderstorms have been previously shown in Figures 19, 27 and 28. Early stages of squall line activity will often appear like the thunderstorms over the Sierras in Figure 19. Well developed squall lines are more likely to appear similar to the area labeled A in Figure 28.

While examples have not been found in the literature thus far, the forecaster is encouraged to be alert for signs of incipient squall lines in satellite photographs. It would seem likely that for a short while incipient squall lines will show themselves as lines of cumulus clouds not yet having reached the thunderstorm stage and not yet within range of radar or surface weather reporting facilities.

B. Topographic Effects.

1. Mountain Ridge Clouds.

Because of their usually small size, and because of the usual distribution of ground observing stations, it is often difficult to determine from conventional data the presence or absence of orographic clouds over mountain ridges. The satellite is an ideal tool for determining whether or not these clouds are present. However, there is sometimes the difficulty of distinguishing between snow and clouds over mountains.

Figure 31 shows a bright area over the Sierras which has been established with reasonable certainty as being only snow without clouds. Figure 32 also shows a bright area over the Sierras, but covering a larger area than the snow in Figure 31. Barring a significant difference in the area of snow between the two, the obvious approach is to subtract the bright area in Figure 31 from that in Figure 32 and assume that the remainder is clouds.

As a different kind of example, Figure 33 shows the sometimes observed cloud-free area over the Columbia River Basin in the Pacific Northwest. Clouds extend from off the coast eastward over the Cascades but are dissipated in the down-slope flow from the Cascades into the Valley.

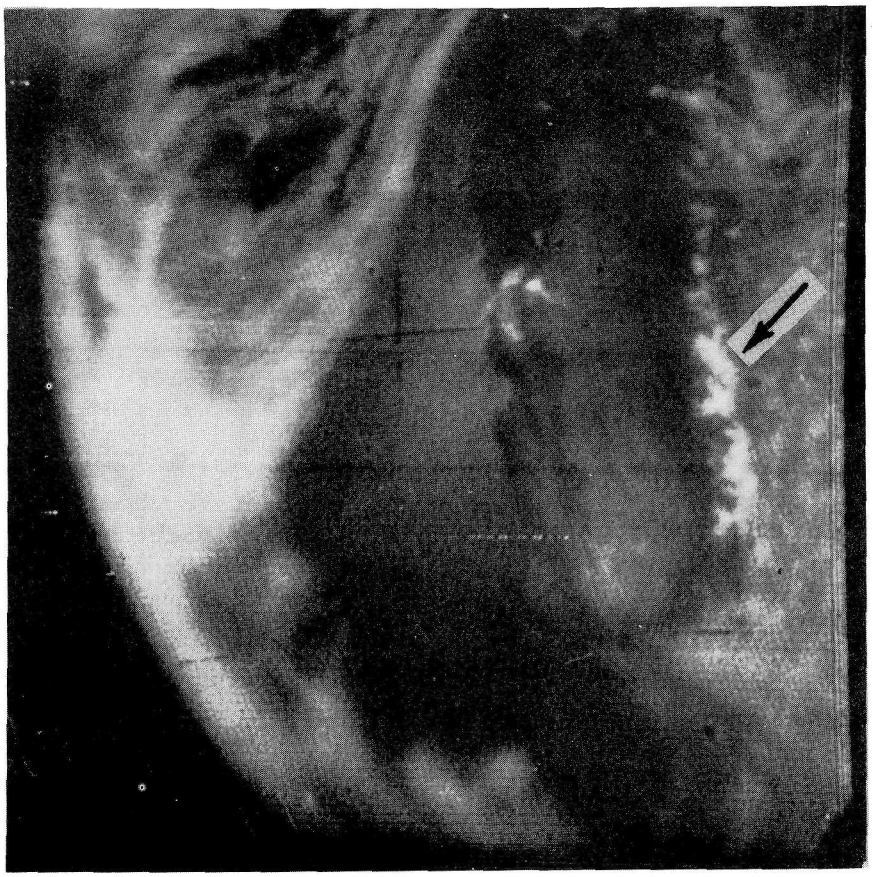


Figure 31. TIROS view of California. The arrow points to a bright area over the Sierras which has been established as being snow over the higher elevations.

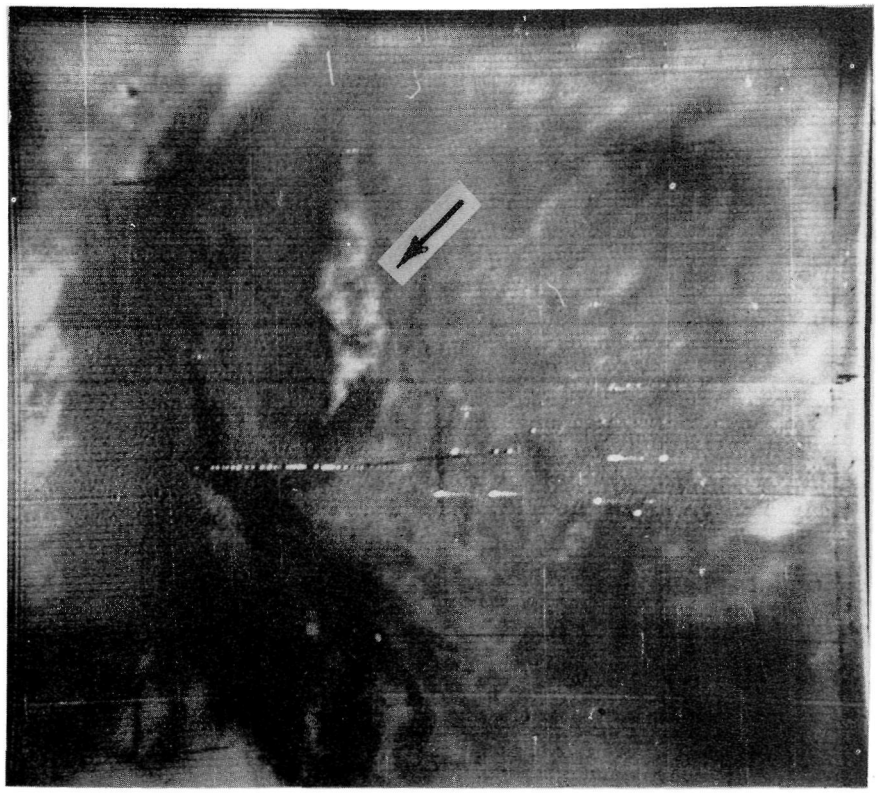


Figure 32. TIROS view of California. The arrow points to a bright area over the Sierras. Comparison with figure 31 suggests that at least part of this area consists of clouds.

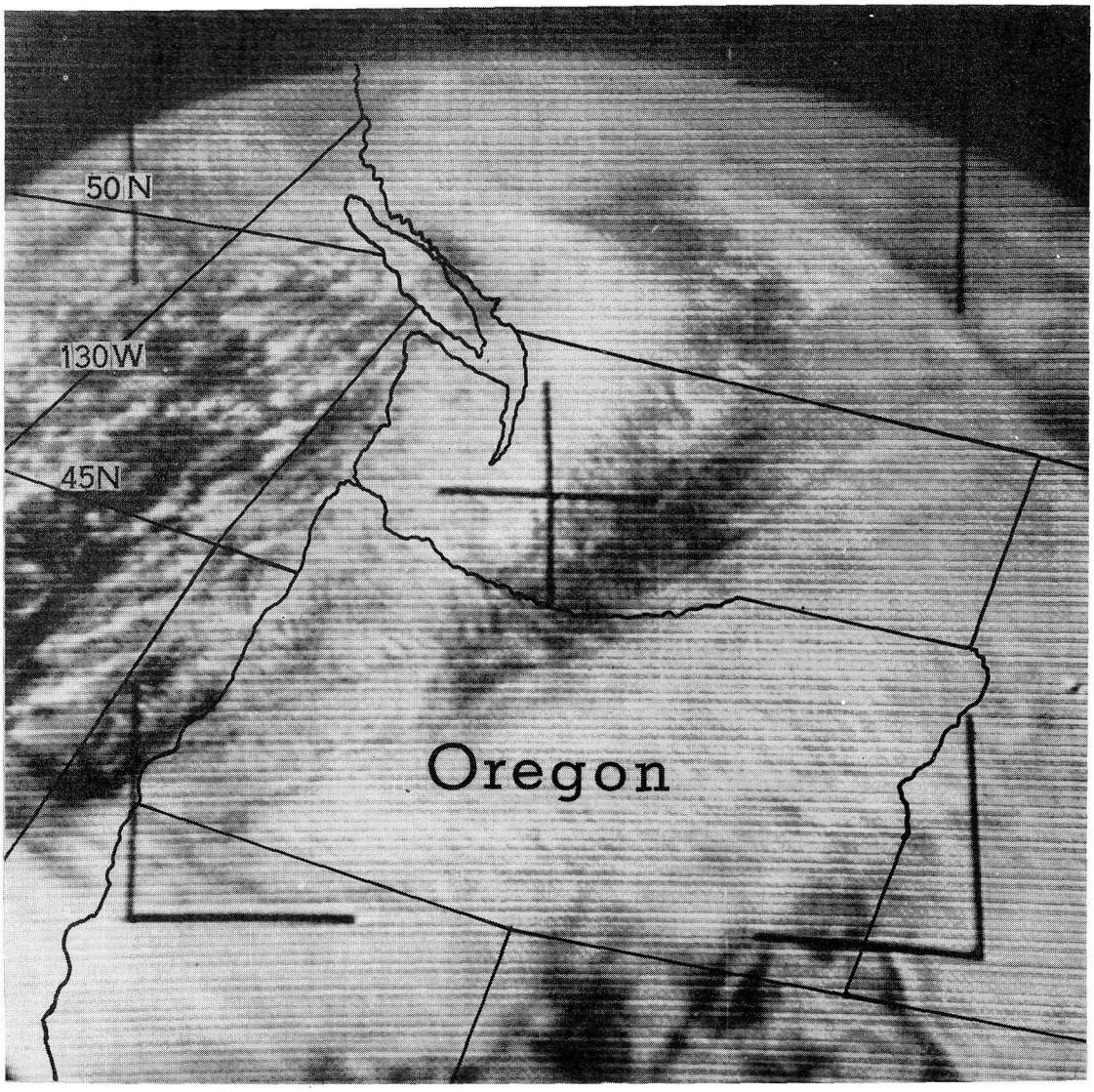


Figure 33. TIROS VI view of Pacific Northwest on December 2, 1962. Note especially the relatively cloud free area in the Columbia River Basin.

2. Mountain Wave Clouds.

Mountain wave clouds have been discussed from the standpoint of their relationship to the large-scale wind field in Section III-E. An example of mountain wave clouds to the lee of the Appalachians was shown in Figure 20. Aside from these large-scale implications, the mountain wave is also significant for purposes of pilot briefing and short-period forecasting. It has long been known that the mountain wave is associated with atmospheric turbulence. Recent investigation has suggested that where mountain wave clouds are observed in satellite photographs, a high incidence of turbulence has been reported by pilots flying in those areas. These investigations are continuing.

3. Valley Fogs.

In Figure 34 can be seen an area of fog and low stratus clouds over the San Joaquin and Sacramento Valleys. Our ability to establish the precise boundaries of these areas is limited only by our ability to establish the geographic coordinates on the photograph. It should be pointed out that in this case it is not possible to distinguish between fog and stratus on the one hand and higher clouds on the other hand from the brightness and texture of the image alone. However, the available conventional observations, together with the fact that the bright area has much the shape of the valley, and the fact that both the coastal range and the area immediately west of the Sierras are relatively cloud free, give substantial support to the conclusion that this is in fact an area of valley fog and stratus.

In cases like this, the satellite photograph completes the fragmentary picture given by conventional observations in a spectacular way. The surface observations reveal that this is an area of low clouds and fog but are incapable of indicating its areal extent with any precision. This precision can be furnished by the satellite data.

4. Coastline Effects.

Conventional observations are often deficient in revealing the distribution of clouds near the coastlines. There are frequent discontinuities in cloud amounts or organization at coastlines. With most of the conventional observations on the land side and few or none on the water side, these discontinuities escape detection. Satellite photos reveal these discontinuities (or lack thereof) very well. The use of the photographs for this purpose is facilitated since often the coastline itself is discernible in the photo.

Figure 35 shows clouds off the coast of Oregon and northern California. At some places the clouds extend a short distance inland. In other places the clouds end on or a short distance off shore. Moreover the character of the cloud mass varies from one area to another. Most of the Washington Coast and adjacent waters are free of clouds. These

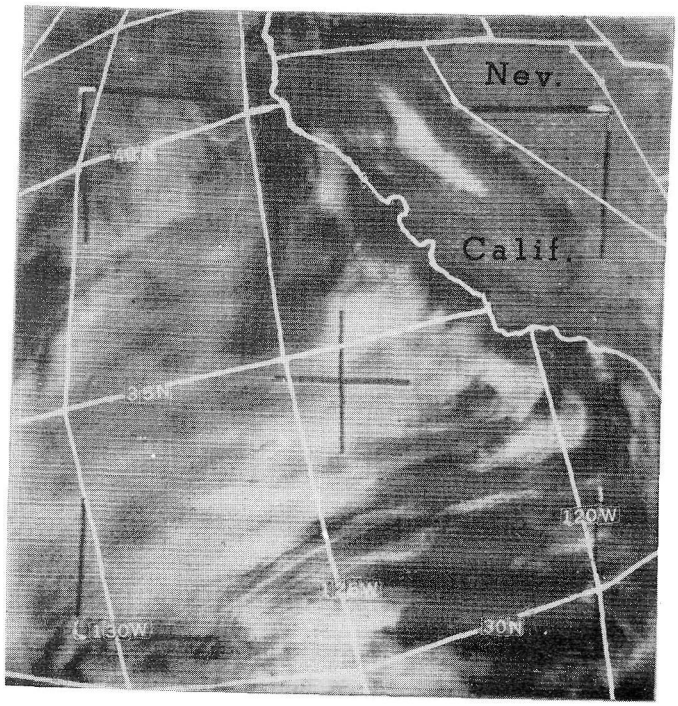


Figure 34. TIROS V view of California and adjacent waters on December 6, 1962. Note especially the area of stratus and fog in the San Joaquin Valley.

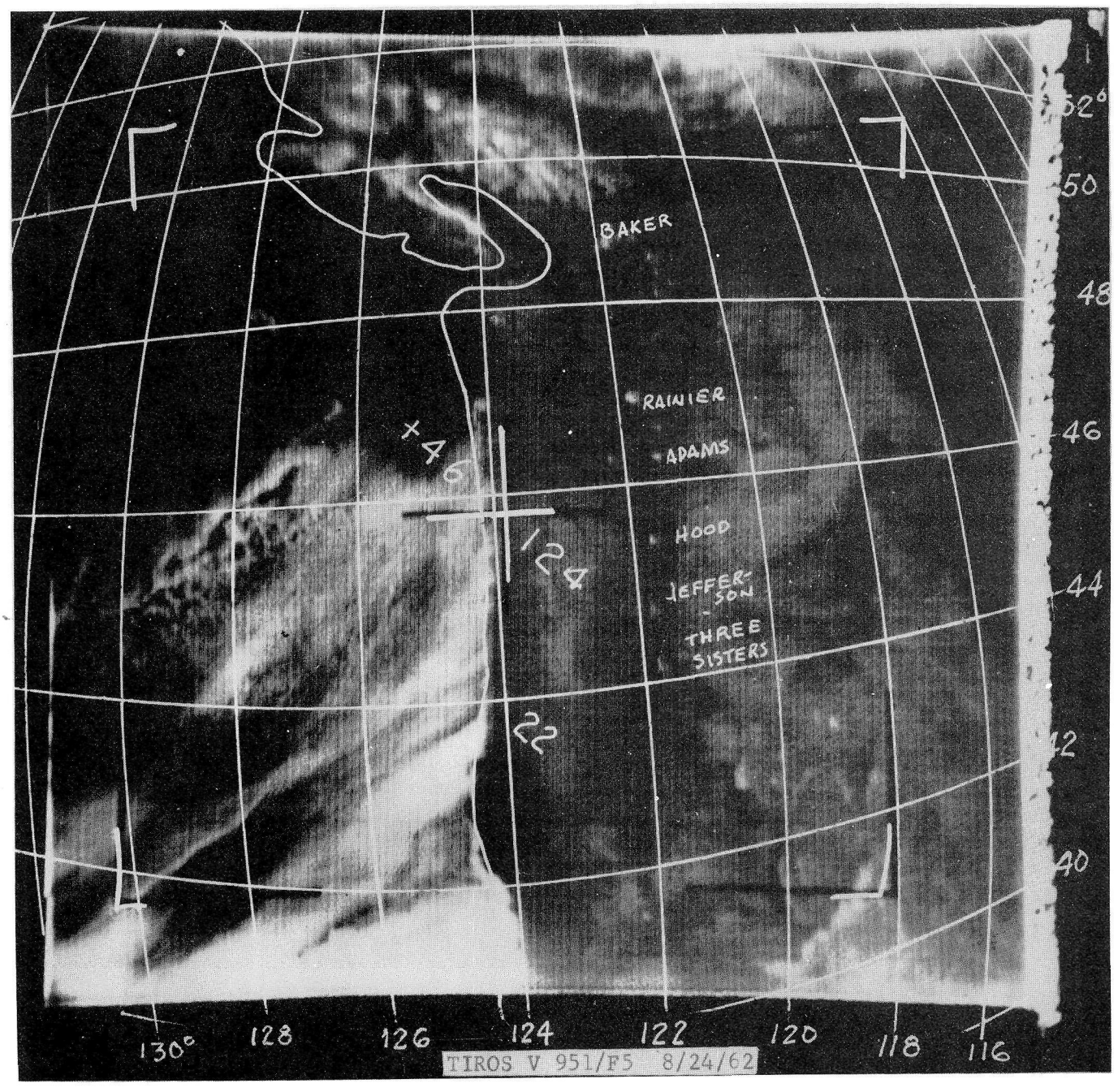


Figure 35. TIROS V view of the Pacific Northwest.
Photo taken August 24, 1962.

satellite data complement conventional data in a rather spectacular and obvious way.

Figure 36 shows the distribution of clouds in the area of Lake Michigan. Much of the southern portion of the Lake is cloud-covered with the exception of the extreme southern tip. There is also a cloud-free strip over land extending around much of the Lake. A marked exception is the bright area of clouds on the northwestern side of the Lake. These clouds are over land and extend to the shore of the Lake. Again, the manner in which these data complement conventional data is striking.

V. SUGGESTED OPERATIONAL PROCEDURES

A. Over Oceans.

Assuming the generalization that the greatest need from cloud data over oceans is in the synoptic scale, it is suggested that the available nephanalyses be transposed to the appropriate sea-level synoptic analysis. An important factor here is that both are on conventional map projections. Transposition of the nephanalysis to the conventional chart is therefore relatively easy, and the cloud data are placed within its broad area synoptic setting. The same procedure will probably be applicable to pictures acquired by direct readout even though a certain amount of rectification will be necessary in transposing the cloud data to conventional analyses. In addition, there may be some value in transposing conventional data to the direct readout picture. This is most likely to be the case where there are details in the photo which are not retained in the nephanalysis but still contain some useful inference in terms of synoptic scale parameters. Additional experimentation is required to determine optimum procedures.

In addition, the International Aviation Forecast Centers at New York and Honolulu (and possibly others) have used satellite cloud data as an effective tool for briefing international flights. If an up-to-date nephanalysis or photograph is available covering all or a portion of the flight route, the briefer includes a copy with the standard flight folder. The pilot's acceptance of this briefing tool has been enthusiastic.

B. Over Land.

At least over the 48 contiguous United States there is some question that routinely transcribing large-scale cloud patterns to operational synoptic charts is a useful procedure. As has previously been suggested, there is already a good deal of this kind of information available and at a greater frequency than is likely to be the case with satellite information for some time to come. There will be many times, however, when it is important to know, either for forecasting or flight briefing, where the precise boundary of a synoptic-scale cloud system lies. If so, this portion of the satellite data is probably most appropriately transposed to the Weather Depiction Chart. At other times, it may be of practical significance to know something about the organization of cloud elements within a particular

Figure 36. TIROS V view of the Great Lakes. Note especially the cloud-free strip around much of Lake Michigan.

cloud mass. If so, this likewise is most appropriately transposed to the Weather Depiction Chart. These two are somewhat arbitrary examples but chosen because in both cases these features of the synoptic-scale cloud systems are usually not revealed by conventional data.

General procedures for synthesizing the smaller scale detail of cloud information with conventional data will necessarily depend on local on-station procedures. At stations where expanded scale sectional charts are plotted and analyzed (such as suggested in OFDEV Technical Note No. 7) the appropriate detail of satellite cloud information is probably best transposed to this chart. What detail to transpose and how it is best done will depend on the nature of the meteorological situation as well as on the nature of the forecast problem.

At times it will be useful to shade on the locally plotted sectional chart with the maximum possible precision certain cloud masses as revealed by satellite photos. This will be especially true in situations where the same area is viewed on two or three adjacent satellite passes. These can then be compared and motions and changes in the cloud masses determined directly.

There are times when satellite photos reveal early stages of squall line formation that are not yet within range of radar or surface observations. Subsynoptic scale features such as this are also probably best transcribed onto the local sectional chart.

These suggested operational procedures are cited for purposes of illustration. At this stage in the development of the operational use of satellite data, it is neither possible nor perhaps desirable to prescribe specific procedures for all kinds of situations. The forecaster must decide what is best and for this purpose the following principles are suggested as general guidelines:

1. Satellite data become most useful when fully integrated with meteorological information from all other sources. Because of this, transposing satellite cloud data to synoptic charts is very desirable. This has the advantage of assembling as much pertinent data as possible on one chart.

2. On the other hand, transpose only such data as has prospect of being useful. Time is a precious commodity for the operational forecaster, especially during periods of critical weather. He must therefore attempt to do those things which hold most promise of being productive.

VI. INFRARED RADIATION DATA

Infrared radiation data from TIROS satellites have not been available operationally. However, operational availability of data from a high resolution (about 5 miles square) infrared radiation sensor is a part of the NIMBUS design. When such data become available, it will allow an approximate determination of the tops of the major cloud masses as well as generalized cloud patterns at night. These data will not be available on direct readout at field stations but will be transmitted through NMC or some other central source.

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