Some Uses of High-Resolution GOES Imagery in the Mesoscale Forecasting of Convection and Its Behavior

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ABSTRACT

The high-resolution satellite imagery presently available from the Geostationary Operational Environmental Satellite (GOES) gives us a unique view of convective activity. This paper addresses some of the mesoscale phenomena, revealed in both pictures from GOES and in movies made from those pictures, which are important in the initiation and maintenance of convection. Specific attention is given to the organization of convection into lines and the importance of those convective lines in subsequent thunderstorm formation. The place where two convective lines merge almost invariably marks the location of intense convective development; under the right conditions, that activity will be severe.

1. Introduction

The Geostationary Operational Environmental Satellite (GOES)[1] observes the earth and its cloud cover in two channels, one in the visible spectrum (0.55–0.75 μm) and one in the infrared (10.5–12.6 μm). The infrared channel provides 8 km resolution[2] data both day and night, while the visible channel provides imagery with a resolution of 1 km during daylight. Normal viewing frequency for the satellite is once every half-hour. Imagery of this high a resolution gives us the unique ability to continuously observe the clouds and their behavior on the mesoscale. Many of the mesoscale phenomena important in the initiation and maintenance of convection, such as the sea breeze (Pielke, 1974), dry lines (Rhea, 1966), mesoscale high pressure systems (Fujita, 1963), areas of convective cloud merger (Woodley and Sax, 1976), lake breezes (Lyons, 1966) and areas of organized convective development (Miller, 1972) to name but a few, which the forecaster previously tried to infer from macroscale patterns, are readily detectable in GOES imagery. Analyses, based on movies using GOES pictures, suggest that there is little, if any, random aspect to thunderstorm development. Among the factors that exert a strong influence on the initiation and maintenance of thunderstorms to be addressed in this paper are terrain-induced convective lines, convective cloud area mergers and convective line intersections.

When using satellite imagery in preparing a mesoscale convective forecast, all available data must be integrated. This includes determining the different parameters that may control convective development on a given day. The meteorologist then uses the frequent interval satellite imagery together with other sources of mesoscale meteorological information (Pautz, 1971) for application to the current situation.

2. Convective development due to land and water interfaces

Under the right meteorological conditions, terrain exerts a pronounced influence on convective development (Defant, 1951; Munn, 1966). The distribution and extent of terrain-induced convection is critically dependent on the strength and direction of the wind in the lower layers of the atmosphere. There are two main reasons for this: 1) surface frictional differences combined with the overlying air's trajectory will lead to the generation of areas of low-level convergence and divergence (Estoque, 1962), and 2) a local heat or moisture source's effectiveness in aiding convective development is in large part determined by the amount of time air parcels spend under the influence of that source (Munn, 1966; Lyons and Olsson, 1973; Malkus and Stern, 1953). Although convective cloud development due to terrain influences is often very complicated, many of the cloud patterns are easier to understand when viewed with high-resolution visible GOES imagery. This is because the 1 km resolution of the imagery is close to the cumulus cloud scale, and the frequent interval between pictures allows one to observe convective development from its earliest stages through maturity.

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[1] More detailed information on GOES and other NOAA satellites may be found in a paper by Ludwig (1974).

[2] Throughout the paper, resolutions given refer to those at the satellite subpoint. Resolution decreases as one moves away from the satellite subpoint; for example, a 1 km resolution at the subpoint (for a satellite at 75°W) degrades to 1.14 km in southern Florida and 1.51 km in central Oklahoma.

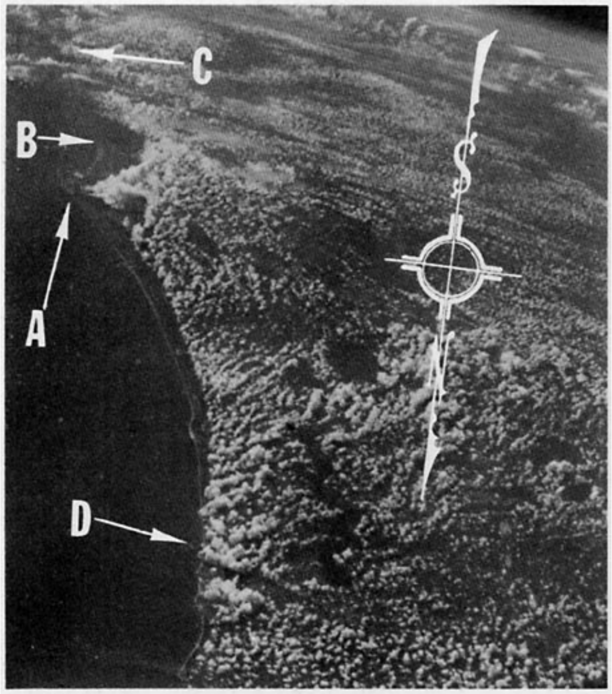
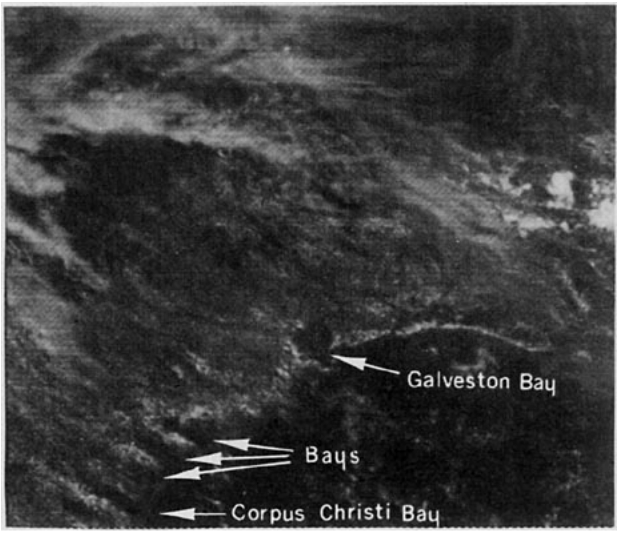


FIG. 1. Gemini 5 photograph for 1531 GMT 22 August 1965.

The sea breeze, a consequence of differential heating between land and adjacent water, has been one of the most widely studied of any terrain phenomena (Haurwitz, 1947; Defant, 1951; Neumann, 1951; Estoque, 1962; Frizzola and Fisher, 1963; Hsu, 1970; McPherson, 1970; Pielke, 1973, 1974). Those authors point out a variety of factors that influence the development of the sea breeze. Among those factors are the direction and strength of the gradient wind, the shape of the coast line, friction, the Coriolis effect, the stability of the air mass and the land and water temperature difference. The latter three will not be addressed here.

The shape of the coast line is one of the major factors that determine the distribution of convective cloudiness along the sea breeze front (Neumann, 1951). Different curvatures in a coast line cause areas of con-



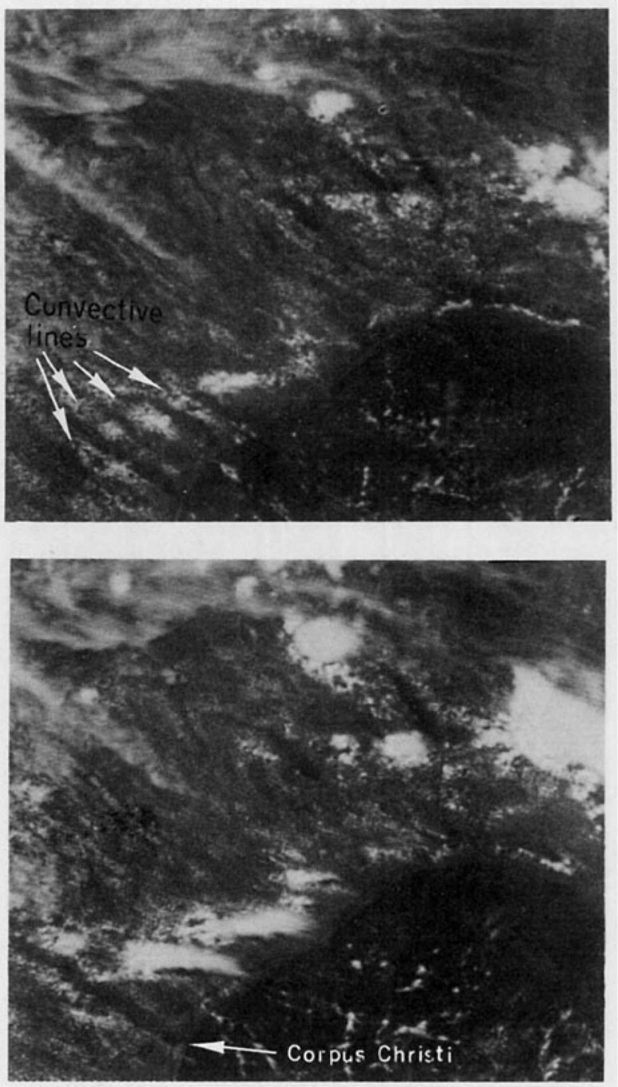


FIG. 2. GOES-2, 1 km visible imagery, 27 May 1975: (a) 1715 GMT, (b) 1845 GMT, (c) 1945 GMT.

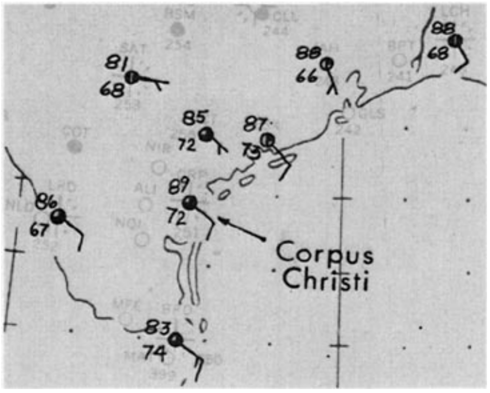
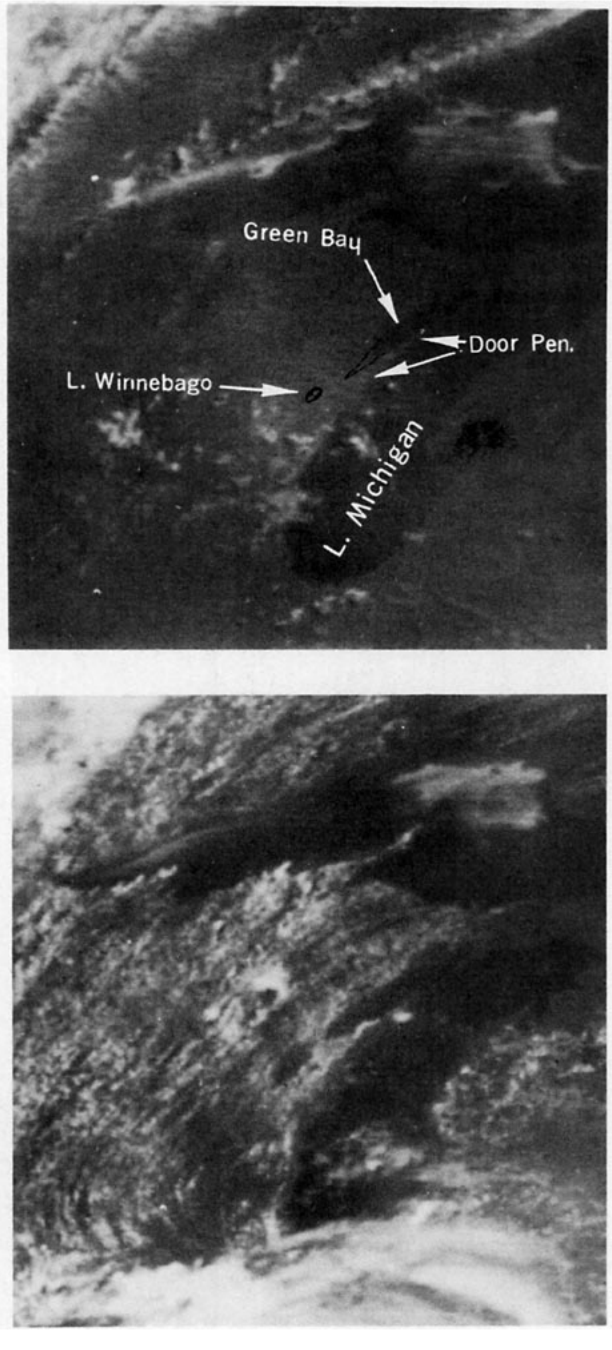


FIG. 2d. Surface data for 1800 GMT 27 May 1975.

vergence or divergence along the sea breeze front, thus leading to a local strengthening or weakening of cumulus activity along that front. An analogy may be drawn with that of lenses in optics: where the coast line is convex toward the body of water, there is an enhancement of the convergence along the sea breeze front as it moves inland, while where the coast line is concave just the opposite occurs. As is pointed out by Pielke (1974), "Local maxima in vertical motion form in regions where the curvature of the coast line accentuates the horizontal convergence created by the differential heating between land and water." Additionally, a small peninsula (for example, the Cape Canaveral and Apalachicola areas of Florida) is generally an area of earlier strong convective development along the breeze front because the breezes formed along opposing shores merge near the peninsula's center. The importance of merging convective cells is receiving considerable attention as one of the more important phenomena accompanying the intensification of convection and heavy rainfall (Simpson and Dennis, 1974; Woodley and Sax, 1976; Oliver and Scofield, 1976; Lemon, 1976).



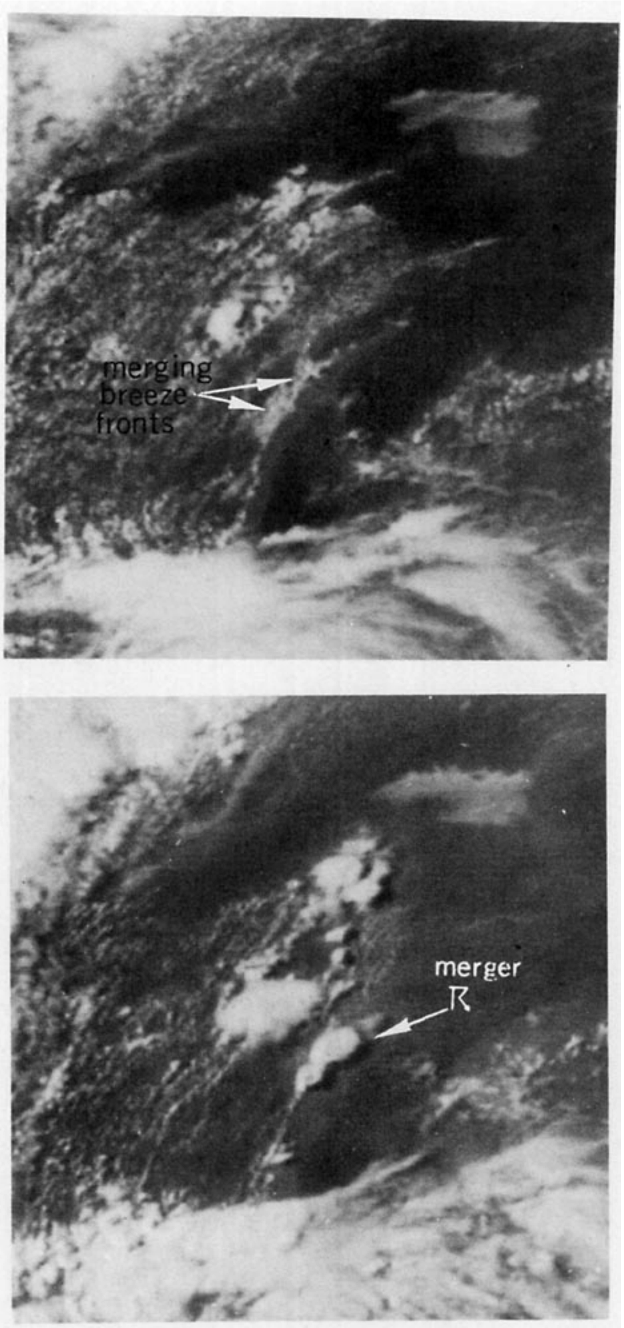


FIG. 3. GOES-1, 2 km visible imagery, 1 August 1975: (a) 1500 GMT, (b) 1830 GMT, (c) 1930 GMT, (d) 2130 GMT.

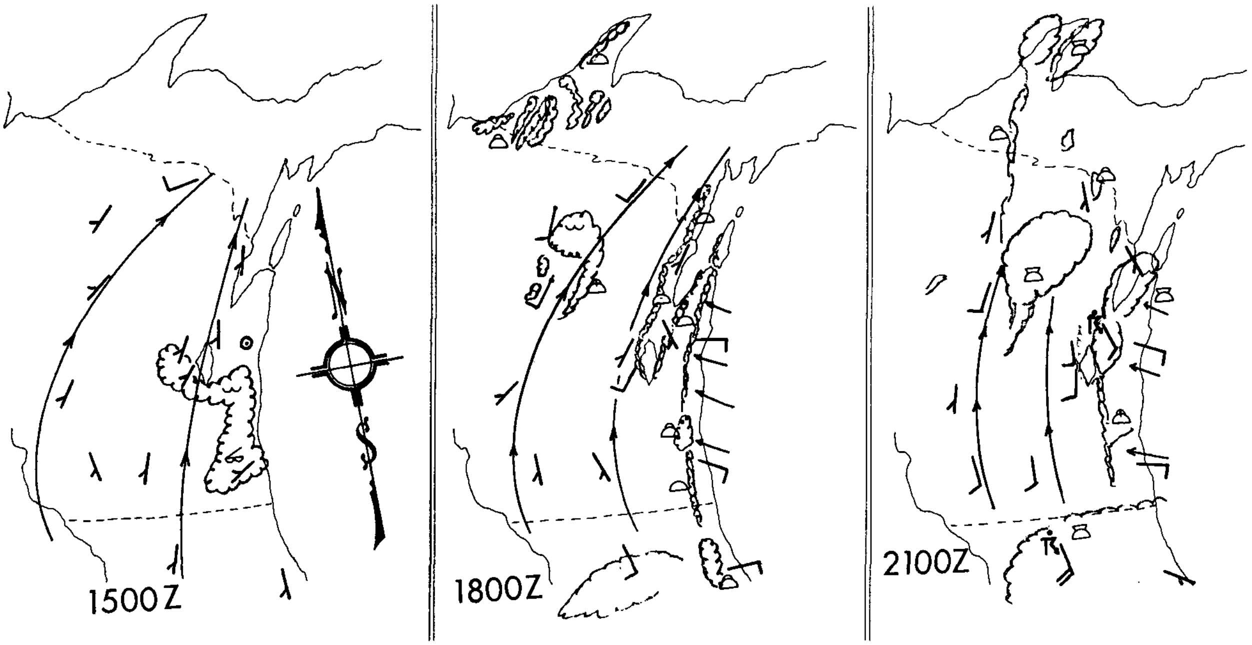
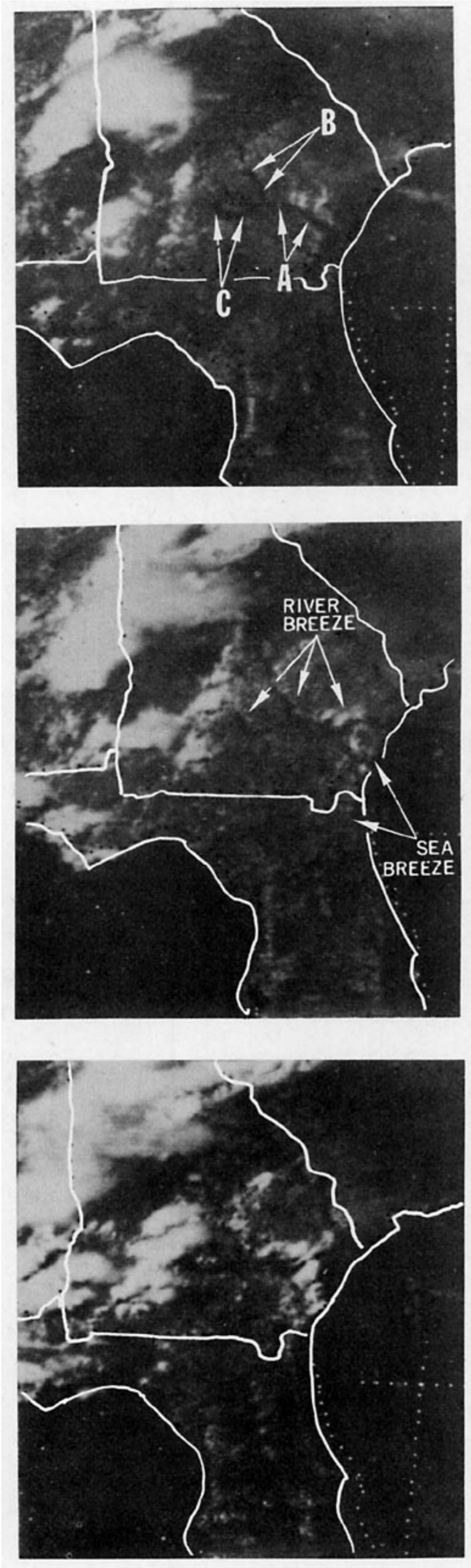


FIG. 3e. Surface wind and streamlines over Wisconsin for 1 August 1975 at 1500, 1800 and 2100 GMT. Cloud types and locations are extracted from Figs. 3a, 3b and 3d.

The effect of the coast line's shape, coupled with the gradient wind flow, can be seen in Fig. 1. Enhanced convective cloudiness near the coast at Cape Kennedy (A) is due to the peninsula effect, while to the south at (B) where the coast line has a concave curvature, the sea breeze has penetrated several miles inland and convection is less developed. Looking further south, to the Miami and Palm Beach areas (C), convection is found closer to the coast line because of its convex shape. In the Jacksonville area (D), the sea breeze convection is near the coast even though the coast line has a concave shape; this is because of the gradient wind. With a surface ridge oriented east–west across Florida, a light onshore flow south of Cape Kennedy changes to an off-shore flow to the north. Thus the inland penetration of the sea breeze north of Cape Kennedy is gradually diminished as one goes north due to the increasingly offshore component of the gradient wind.

Fig. 1 illustrates how a fairly uniform coast line gives rise to a rather continuous sea breeze which nearly parallels the coast line. As is pointed out by McPherson (1970) in his investigation of the effect of a bay on the sea breeze for a condition of no synoptic-scale flow, the effect of an irregularly shaped coast line on the sea breeze has received little attention. Daily viewing of GOES satellite movies of the sea breeze along the southern Texas Gulf Coast, which has a large number of bays and inlets, has shown that an irregularly shaped coast line has a pronounced influence on convective development along the sea breeze front. The direction of the low-level wind becomes very important in determining where inland convection forms along the sea breeze front. Envisioning an irregular coast line as a series of small peninsulas, convective clouds form downwind from the peninsulas while clear zones extend downwind from the bays. These downwind clear zones may extend up to a few hundred kilometers inland with thunderstorms and strong convection immediately adjacent to them along one of the downwind convective cloud lines. Figs. 2a–2c illustrate this type effect; note the low-level wind field shown in Fig. 2d. Inspection of the figures readily shows the clear areas downwind from the bays and the convective lines downwind from the peninsulas. In Fig. 2c, note how the clearing downwind from Corpus Christi extends over 200 km inland, while thunderstorms have formed along some of the downwind convective lines. Prior to thunderstorm formation along the convective lines (Fig. 2b) there is an enhancement in the convective cloudiness where the thunderstorms later develop. This is typical to thunderstorm development along a line and may be used to help in the short-range forecasting of thunderstorm development.

Convective development due to land and water interfaces is not limited to coastal areas, but also occurs regularly around lakes (Lyons, 1966). The factors influencing convective development are the same as those for the sea breeze. However, the low-level wind field becomes increasingly important the smaller the lake with which one is dealing. In Figs. 3a–3d, one can follow the development of a lake breeze front along Lake Michigan's western shore. Notice that both Lake Winnebago and Green Bay develop breeze fronts along



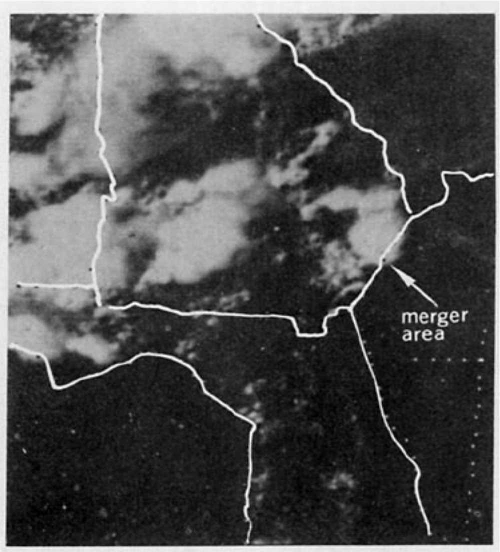


FIG. 4. GOES-1, 2 km visible imagery 26 May 1975: (a) 1730 GMT, (b) 1830 GMT, (c) 1930 GMT, (d) 2300 GMT.

both shore lines. This is a case with a low-level south to southwesterly flow, as shown in Fig. 3e. Frictional effects (Petterssen, 1956) with this wind should cause the breeze convergence zones to form close to the western shore of the Door Peninsula and further inland along its eastern shore. These breeze fronts develop in that fashion. Since the flow of air remained nearly parallel to the peninsula during the day, the breeze-generated convergence zones persisted long enough for convective activity to develop. Note the large thunderstorm that formed over the Door Peninsula's western shore where the two breezes merged.

While the effects of oceans, lakes and even cities (Changnon, 1976) on convective development have received considerable attention, relatively little work has been done concerning the effects of rivers and river basins on convective development. Dubinskii (1956) found that the Dnieper River Valley exerted a considerable influence on the microclimate in its immediate vicinity, depending on the local weather conditions. Later, Liakhov (1970) found that the Ob River's impact on local climate depended on the speed and direction of the wind over the river basin. GOES imagery has shown that rivers and river basins at certain times exert a considerable influence on convective development. The influence has been most noticeable when the low-level winds were either nearly calm or blowing lightly (generally less than 5 m s^{-1}) parallel to the river basin. The effect of a complex of rivers on convective development is graphically illustrated in Figs. 4a–4d which show convective development in the vicinity of the Altamaha (A), the Oconee (B) and the Ocmulgee (C) rivers in Georgia. Each river shows up nicely because of the formation of fair weather cumulus clouds over the warmer land, but not in the cooler air along the river. On this day, winds at the

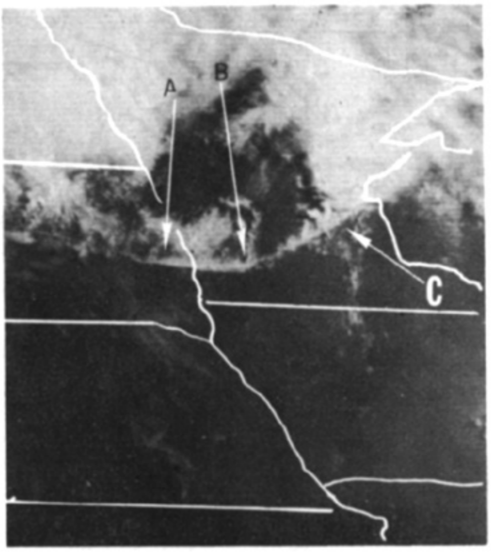


FIG. 5a. GOES-2, 1 km visible imagery, 29 June 1975, 1445 GMT.

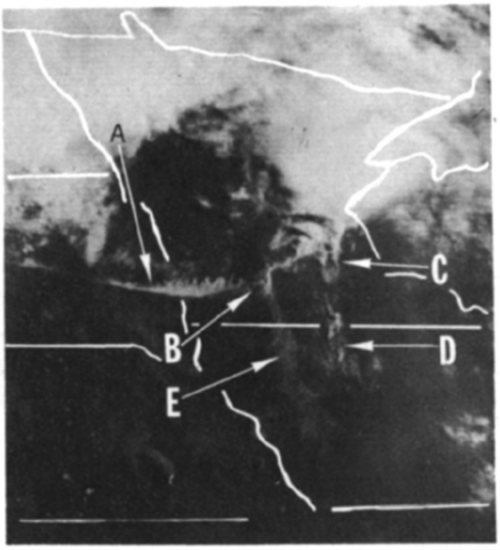


FIG. 5c. GOES-2, 1 km visible imagery, 29 June 1975, 1545 GMT.

surface were light, being generally southerly at less than 3 m s^{-1}. Each of the rivers has a breeze front defined in the cloud field along its northern shore by midday, with some of the convection on the river breeze fronts reaching thunderstorm size. Note the inland penetration of the sea breeze along the Georgia and Florida coasts in Figs. 4b–4d and the large thunderstorm that develops where the sea breeze merges with the Altamaha River's breeze front. Intensification of convection produced at the intersection of a terrain-induced convective line with another organized convective line has previously been noted by Shenfield and Thompson (1962), Boyd (1965), Lyons (1966) and Chandik and Lyons (1971).

3. Convective mergers and intersections

In the previous section it was shown that the merger of two terrain-induced convective lines located a point for intensification of convective activity. As one might expect, the merging of cumulus cloud lines and the subsequent intensification of convection is not confined to terrain-induced convective lines. Previous satellite studies using 8 km resolution satellite imagery, by Purdom (1971) and Oliver and Purdom (1974), have shown that in dynamic regimes when thunderstorms tend to form in lines, the lines were often detectable in satellite imagery a few hours prior to thunderstorm formation along the line. This is not surprising when one considers the case studies presented by Sasaki

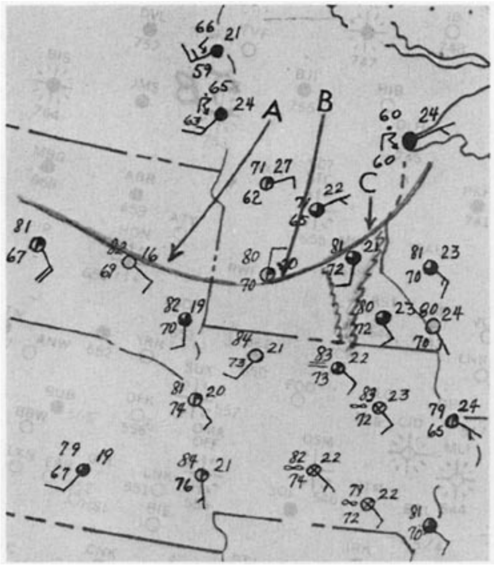


FIG. 5b. Surface data for 1500 GMT 29 June 1975, with boundary A–B–C from Fig. 5a located within data.

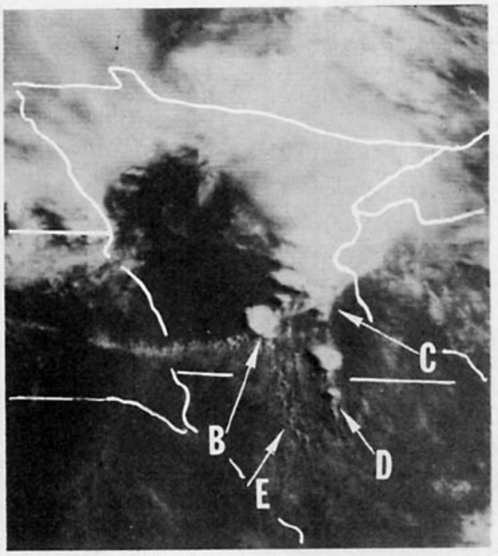


FIG. 5d. GOES-2, 1 km visible imagery, 29 June 1975, 1645 GMT.

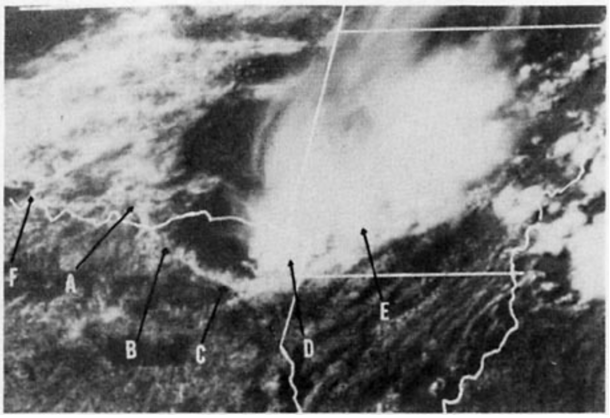


FIG. 6a. GOES-1, 1 km visible imagery, 26 May 1975, 2000 GMT.

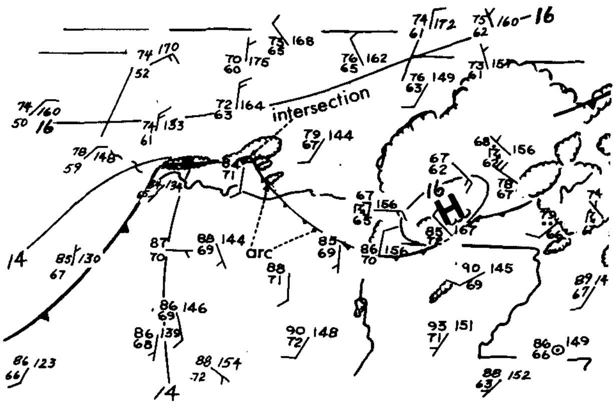


FIG. 6c. Surface analysis for 2100 GMT 26 May 1975. Selected clouds and cloud boundaries, extracted from Fig. 6b, are included with the analysis.

(1973) in which he found that "surface moisture convergence began several hours earlier than the severe weather systems reached their mature stage (precipitation echo, funnel and tornado)."

The near order-of-magnitude increase in spatial resolution afforded by GOES has further revealed that new thunderstorm formation, as well as the more intense and long-lived thunderstorm, often occurs where a line intersects another convective line or merges with an area of enhanced cumulus activity. This same effect has previously been shown by Chandik and Lyons (1971), Miller (1972) and Purdom (1973a).

An example of merging convective cloud lines and new thunderstorm formation is shown in Figs. 5a–5d. In Fig. 5a, a convective boundary produced by earlier thunderstorm activity in Minnesota extends from A–B–C. Active thunderstorms are still in existence in eastern Minnesota along the line northeast of C. Old boundaries of this type should be monitored closely; according to Miller (1972) they are preferred regions for new thunderstorm development. Close scrutiny of surface data (Fig. 5b) shows no reason for new thunderstorm formation at one point along the boundary rather than another. However, it is possible to isolate those areas of new thunderstorm development by using GOES imagery and the concept of merging convective lines. By 1545 GMT (Fig. 5c) two convective lines (CD and BE) have developed to the south of the boundary and are merged with it. Note, in Fig. 5d, the thunderstorm formation that results from this merging. These lines (CD and BE) were not terrain-related. Most probably they represent areas of deeper and more organized moisture convergence, in parallel to the findings by LeMone and Pennell (1976) relating the fluxes of moisture and momentum in the upper subcloud layer of tropical cumulus to cloud distribution. However, if they had been terrain-induced, the same results should have occurred.

4. Thunderstorm-produced cloud lines and their interaction with other boundaries

The mesoscale high pressure system (mesohigh) and how it is produced in an intense thunderstorm area has been explained by Fujita (1963). Using satellite

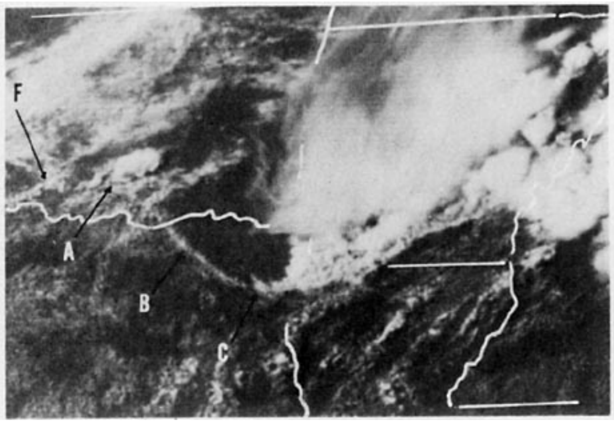


FIG. 6b. GOES-1, 1 km visible imagery, 26 May 1975, 2100 GMT.

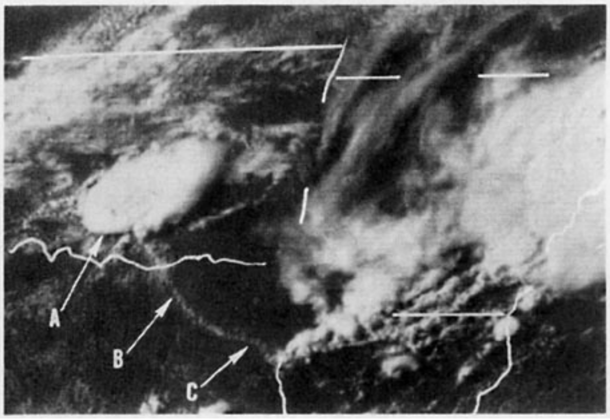


FIG. 6d. GOES-1, 1 km visible imagery, 26 May 1975, 2230 GMT.

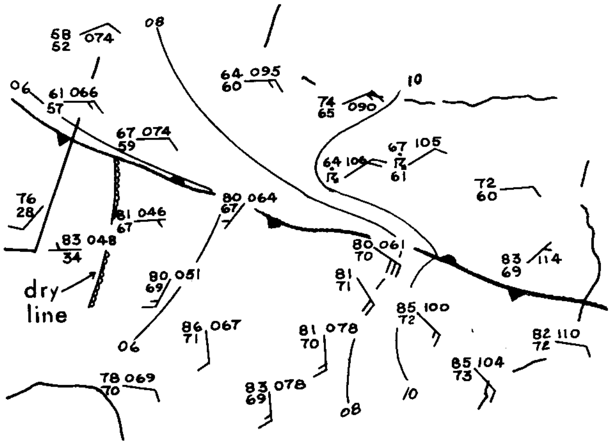


FIG. 7a. Surface analysis for 1800 GMT 25 May 1976.

imagery, Purdom (1973) showed the leading edge of the mesohigh appeared as an arc-shaped line of convective clouds moving out from a thunderstorm area. Later, Purdom (1973a, 1974) showed that the intersection of an "arc" cloud with another boundary marked a point with a high potential for intense convective development and oftentimes severe weather. This correlated well with the work of Miller (1972) on the importance of "bubble highs" and their interaction with active squall lines in the production of tornadoes. The ability to precisely locate arc cloud boundaries in GOES imagery and observe their interactions with other boundaries provides the forecaster with important information for use in the short range forecasting of intense convective development. Two cases[3] are given below to illustrate this point.

a. Case 1, 26 May 1975

A stationary frontal boundary extended through central Arkansas into south-central Oklahoma with a weak cold front extending from south central Oklahoma into Texas (Fig. 6c). The stationary frontal boundary (line AF in Figs. 6a and 6b) is located in the satellite pictures by observing the change in cloud character across it: cumuliform clouds to its south and smoother appearing stratiform clouds to its north. In the afternoon, a large mesoscale high pressure system was produced as thunderstorm activity (DE in Fig. 6a) moved southeastward off the stationary frontal boundary. The western portion of the mesohigh shows up as the arc cloud (A–B–C in Figs. 6a, 6b and 6d). The single large thunderstorm area in southeast Oklahoma, at A in Figs. 6b and 6d, developed precisely where the arc cloud intersected the stationary frontal boundary. Although these thunderstorms were severe, no tornado activity was reported with them.

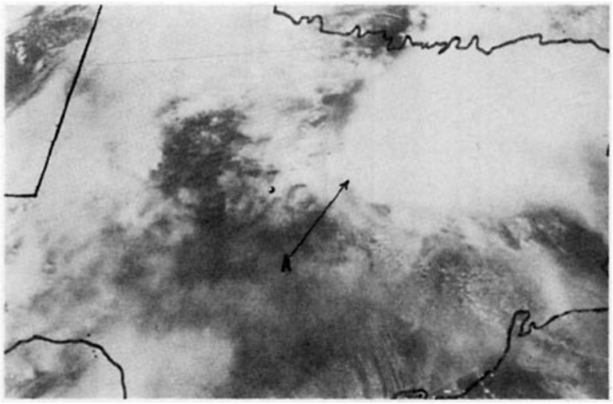


FIG. 7b. GOES-1, 1 km visible imagery, 25 May 1976, 1800 GMT.

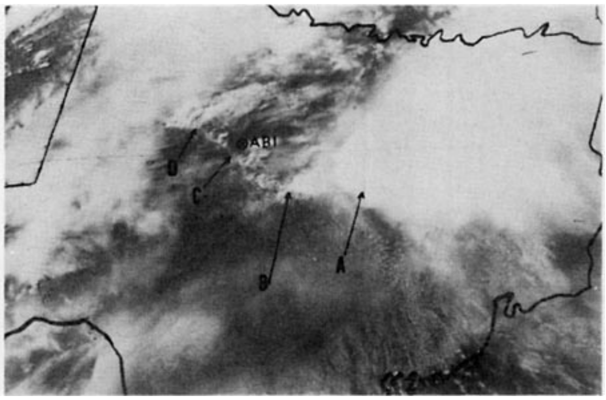


FIG. 7c. GOES-1, 1 km visible imagery, 25 May 1976, 1900 GMT.

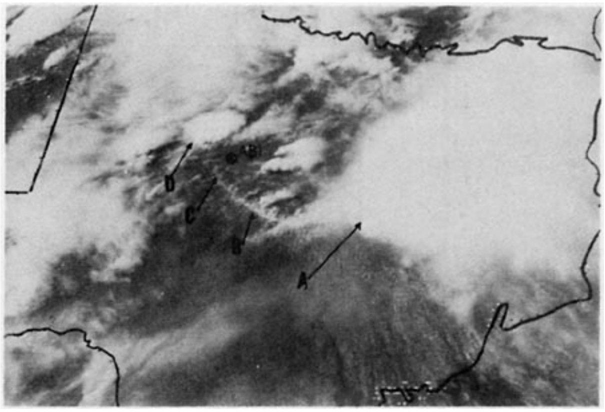


FIG. 7d. GOES-1, 1 km visible imagery, 25 May 1976, 1945 GMT.

b. Case 2, 25 May 1976

May 25th was an ideal day for tornadoes in Texas. A stationary front lay across central Texas with the dry line in west Texas between Midland and Big Springs (Fig. 7a). Inspection of the 1 km resolution GOES picture for 1800 GMT (Fig. 7b) showed a large thun-

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[3] In these cases, surface data are plotted on map bases with the same projection as that of the satellite imagery. In Case 2, winds are gust winds.

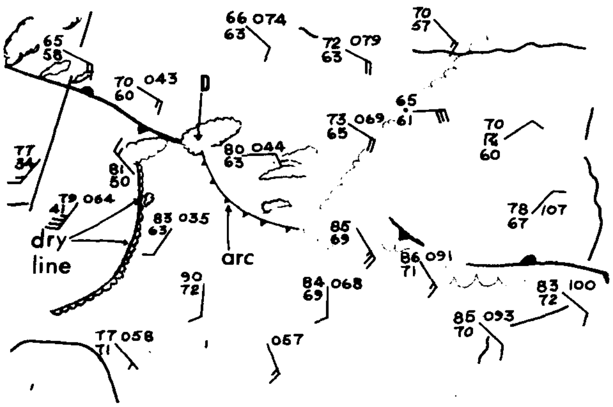

FIG. 7e. Surface data for 2000 GMT 25 May 1976. Limited analysis includes stationary front and dry line locations, as well as selected clouds and cloud boundaries extracted from Fig. 7d.

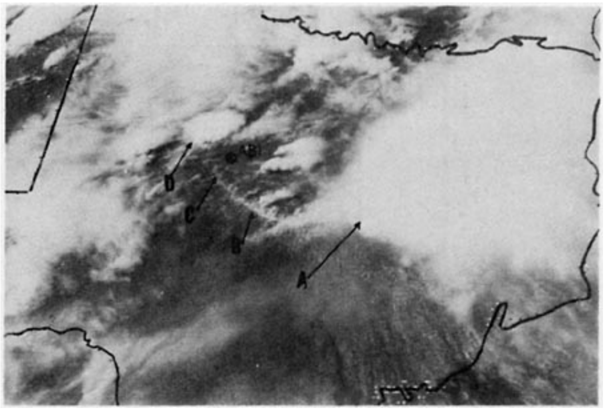

FIG. 7f. GOES-1, 1 km visible imagery, 25 May 1976, 2045 GMT.

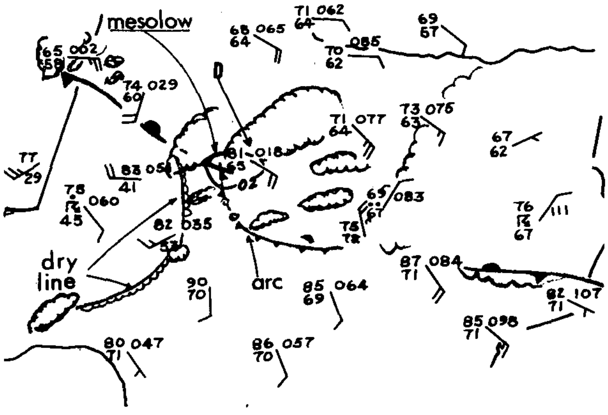

FIG. 7g. Surface data for 2100 GMT 25 May 1976. Limited analysis includes stationary front and dry line locations, mesolow, and selected clouds and cloud boundaries extracted from Fig. 7f.

derstorm area along the front at A. This thunderstorm area was moving to the southeast along the front, and by 1900 GMT had a well-defined arc cloud boundary (B–C–D in Fig. 7c). This boundary played a key role in the tornadic activity that formed later in the day. At 1900 GMT, hourly surface data showed that as the arc moved south of Abilene (ABI), the wind shifted from 210° at 4 m s^{-1} to 90° at 7 m s^{-1}. Enhanced convective activity formed where the arc and the frontal boundary merged at D. The dry line, beneath the middle and high cloudiness in west Texas, was not detectable in Figs. 7b or 7c. By 1945 GMT (Fig. 7d) a large thunderstorm complex had developed at the intersection point D. Fig. 7e is a composite of the 2000 GMT surface data and the convective clouds and various boundaries detectable in Fig. 7d; note that some thunderstorms and convective cloudiness are detectable along the dry line which has started to move eastward. By 2045 GMT (Fig. 7f) the thunderstorm complex at D had moved eastward along the arc into the Abilene area. Between 2045 and 2130 GMT, four tornadoes were reported in the Abilene area; considerable damage was done to farms and homes. As with the 1945 GMT satellite picture, the 2045 picture may be compared with its corresponding surface data in Fig. 7g. Of particular interest is the mesolow at the intersection point of the arc cloud and severe thunderstorm at D. Both Miller (1972) and Magor (1958) point out the importance of the mesolow, formed at the intersection of an instability line with another boundary, for tornadic activity. The large thunderstorm on the dry line to the west of Abilene was severe; however, there were no tornadoes reported with it.

5. Conclusion

The high-resolution satellite imagery from GOES is helping to open the door for a new era in mesoscale meteorology. Many of the mesoscale processes important in the initiation and maintenance of convection are readily detectable in the imagery. Effects of terrain on convective development are often pronounced and show up well in the imagery. Terrain often causes convection to develop in lines, which may interact with other convective lines, thus causing a local intensification of convection. Thunderstorm-produced cloud boundaries, the arc cloud, are easily detected in the imagery. The intersection of an arc cloud with another convective boundary almost always leads to an intensification of convection; when other atmospheric parameters are right (Miller, 1972) severe weather will develop at the intersection point.

The importance of being able to precisely locate areas of organized convective merging and lines of convective intersection cannot be overstated: it can provide the meteorologist with invaluable information about areas which should be monitored for local intensification of convection. According to Woodley and Sax (1976), "the merger process . . . is a key problem in atmospheric dynamics and severe weather prediction"—observations from GOES certainly support that statement.

6. Outlook

Throughout the paper, the phrases "often" and "almost always" appear concerning various convective phenomena. This is because no occurrence statistics have been gathered for the phenomena, but rather the statements refer to the author's experience gained from daily observations of GOES cloud motion movies over the United States during the past two years. We hope to learn more about these phenomena over the next few years as more and more meteorologists use this unique source of data in studying all types of convective phenomena.

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