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ANIMATED SATELLITE IMAGERY OF AN AFRICAN SQUALL LINE DURING GATE

Michael Fortune
Space Science and Engineering Center
University of Wisconsin-Madison
Madison, Wisconsin 53706

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ABSTRACT

The African "disturbance line" is a particularly extensive and long-lived analogue of the mid-latitude squall line, but the modelling of it has suffered from a sparse data network and equally sparse satellite coverage. The complete evolution of one typical African squall line is analyzed and its windfield mapped with the aid of a 48 hour sequence of SMS-1 images on the McIDAS system of the University of Wisconsin. The animated imagery depicts the eventual organization of the disturbance on the sub-synoptic scale and also follows it in a storm-relative reference frame. An analysis from satellite, aircraft, and raob data on 5 September 1974 highlights the shear profile typical of west Africa, and the proximity of a wave trough, as factors in organizing mid-level convergence which the disturbance tends to preserve. Once established, the circulation maintains a series of shorter-lived squall lines, each of which evolves through stages for 6 to 12 hours. As in cases of tropical squalls over the ocean, the momentum of the mid-levels is brought to the surface under an extensive raining "anvil", while the forward edge of this organized downdraft sweeps monsoon air into convective towers that maintain the process.

1. Introduction

The planning report for the Severe Environmental Storms and Mesoscale Experiment, (Lilly, 1977), stated that "only a small fraction of the scientific community is aware of the vast potential of time-lapse satellite imagery for describing severe storms" and recommended, among other things, that "packages" of selected film loops illustrating important physical processes in severe storms be made widely available, and that journal articles describing phenomena in the film animations be published.[1] In the spirit of this recommendation, this article reports a case study of an African squall line based on TV-animated SMS satellite images.[2]

The surface manifestations (Hamilton and Archbold, 1945), synoptic setting (Eldridge, 1957; Dhonneur, 1970), climatology (Aspliden, 1976), and modeling (Dhonneur, 1970; Zipser, 1971) of African disturbance lines have been reported. The author has reviewed the literature in French and English on this phenomenon elsewhere (Fortune, 1977). Recent experiments in West Africa (ASECNA, 1974, 1975) and satellite studies from GATE (Aspliden, 1976; Houze, 1977) have considerably advanced the understanding of squall lines. Nevertheless, the sparse station network has hindered a conventional analysis of these storms through the course of their lifetime. It was felt that continuous SMS imagery, when analyzed on an interactive video terminal, would reveal the dynamics of their rapid and long-lived propagation, and any relation to the synoptic cloud and wind fields. The McIDAS system of the University of Wisconsin (Smith, 1975)

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[1] Project SESAME (Lilly, 1977), Report of the Satellite Data Working Group, pages 231-233.

[2] A 20-minute videotape cassette exhibiting the complete evolution of the storm and the analysis used in the case study is available on request. Contact the Business Office, Space Science and Engineering Center, University of Wisconsin at Madison; the cost is $5. if you supply a blank videotape, and $20. if you purchase a new one. The tape is also available for rental.

was chosen to scrutinize a squall-line disturbance over its two-day lifetime in a data-poor region of West Africa, and to map the inflow and outflow of components of the disturbance.

Several convective systems occurred on September 5, 1974, a day that had been chosen for intensive observation during GATE. One squall line which traversed some 2000 km before expiring over the sea off Dakar was chosen for the case study. Sequences of visible and infrared SMS images encompassing the 48-hour lifetime of the disturbance were analyzed.

The images were taken at half-hour intervals at a resolution of 2 km in the visible and 10 km in the infrared. Most of the animated visible sequences were displayed at 4 km resolution in order to include a large enough area. The brightness, height, area, and growth of cloud elements were measured in order to reconstruct the structure of the system in three dimensions. The manner and speed of propagation were noted, and the environmental windfield was mapped by cloud-tracking.

The satellite imagery was supplemented by surface observations, rawinds, and radiosoundings at Dakar and Bamako as reported in the GATE Quick-Look Data Set (Environmental Data Service, 1976). Useful observations were also made by an NCAR research aircraft, the Queen Air, which skirted the flank of the squall at maturity (1300 GMT).

2. The Evolution of the Disturbance

The long continuous observation of this case reveals that a disturbance line contains a hierarchy of briefer and smaller squall systems. Each system consists of an arc front, numerous convective-scale Cb towers, and an extensive shield of thick cloud referred to as an "anvil" though it is normally thicker than the anvils of mid-latitude storms. The arc front and the Cb towers may or may not appear as distinct forms on the images. Previously considered to be mere severe storms or squall lines, the phenomena are here regarded as synoptic disturbances which bear some relation to the travelling African waves.

The storm originated at 1400 GMT on September 4 from several convective cells arranged in a ring, and it quickly acquired the classic form of an African squall (Latrasse, 1972) (see Figure 1a): on satellite images, a compact, oval cloud mass bright in both visible and infrared, with an arc-shaped leading edge. On infrared images the edge appears to slope back with height; on visible images it casts a distinct shadow. Composed of initially discrete, rapidly developing Cb cells, this edge advanced westward at 16 m/s and trailed a thick "anvil" of middle-to-high cloud. After four hours this system (of Cb's and anvil) covered an area 150 km across, and eventually merged with neighboring systems which formed somewhat later. At least three times through the night of September 4, younger and more vigorous squall systems merge with the main cloud mass which then begins to fade. The main locus of activity propagates discontinuously at some 18 m/s whereas the individual arc fronts march at 12-15 m/s.

The progress of the squall fronts of the most active elements in the disturbance is charted in Figure 2, from its origin at Timbuktu at the site marked ⊗ to its dissipation beyond Dakar. The disturbance encompassed several mesoscale squall lines through various stages of their life cycle. On 4 September the near-simultaneous appearance of Cb cells and the merging of them into a large cloud mass argues for some synoptic-scale factor in its formation.

On 5 September, an impressive squall in this disturbance was observed to evolve through its life cycle from 500 to 1800 GMT on the satellite imagery. (Figure 3 depicts its evolution in a montage of hourly SMS images displayed to show its westward progression). A large cell appears on the 500 IR image at the location marked by ⊕ on Figure 2. The compact, oval-shaped cloud mass grew rapidly for 3 hours, then ahead of the main mass, there formed an arc which is known to correspond to a "roll cloud" at the gust front--the leading edge of the cold air outflow. The process went like this:

a) Before 930 GMT a cloud deck obscured the area ahead where a front might have existed.

b) At 1000 an arc of low cloud is seen 50 km ahead of the main cloud mass. As is moved westward, it appeared to trigger small convective cells which "lagged behind" the arc line as they developed, until they eventually merged with the "anvil".

c) The arc separated from the main cloud. It became a bright band on the visible images (1100 GMT) as the areas just ahead and behind it underwent clearing.

d) The arc remained distinct for over five hours. As it swept through, it gave the appearance of a brush-fire emitting a "pall of smoke" into the anvil. As the cells developed vertically they acquired more easterly momentum, but always moved more slowly than the arc.

e) After 1500 GMT the arc extended laterally. The ends were passive but along the middle, the distinct roll cloud was transformed into a "string of popcorn cells" of all sizes. The anvils of these cells spread in all directions so that the original arc became blurred and lost. The evolution of the arc follows a scheme developed by Purdon (1973) and extended by Gurka (1976) to classify the stages of development of North American squalls from satellite imagery. The early compact, ovoid form has been associated with squalls in vigorous development, and distinct or detached arcs with older storms which may or may not spawn new elements.

Figure 1b is a full-resolution visible image of the squall at maturity. At this time the Queen Air flew its mission along the course shown in the photo, the most numerous rawind soundings were taken (at 1200 GMT), and the SMS satellite took the images on which the windfield was mapped on McIDAS. Note the distinctly convex, bright arc front, the various sizes of convective cells behind it, and to the northeast the anvil cirrus which is rapidly fading. To the southeast is the clear zone which developed behind the anvil after it passed by.

The "anvil" cloud grew in the manner depicted in Figure 4; curve b is typical of several of the successive squalls. The anvil appeared brightest just before the arc formed, and expanded for some six to eight hours as it faded. After some four hours the mesoscale downdrafts (curve a) became established and continued to spread long after the anvil dissipated. (The area under the influence of the downdraft was determined by criteria described in the mass budget analysis).

The squall system lost its vigor when the arc pushed well ahead of the dissipating anvil, and the anvils of the newer cells failed to merge into one shield which before had extended some 300 km. The arc did trigger storms on reaching the coastal confluence line, and more over sea through the night, but the triggering process propagated at the slower rate of the easterly wave trough in which the system was situated after 1200. The merging of "fast" squall disturbances with "slow" wave or cluster disturbances appears to be common (Payne and McGarry, 1977).

To the north of the main disturbance, a "sister squall" formed at 1400 at the site marked by an (*) on Figure 2. The cloud mass grew explosively, some three times more rapidly than the main squall, for ten hours, as the western edge advanced at 25 m/s. When the front overtook the sea-breeze line at 1900, new arcs on the southern flank advanced rapidly over ground that had been free of cloud cover through the day. Three cross-sections of the evolving disturbance were reconstructed (Fig. 5) by plotting McIDAS measurements of cloud height and thickness along a sectional line. Note the nose-shaped configuration of the leading edge, its pronounced slope and rapid advance. The slope is believed to result from the vertical development process of a train of Cb plumes behind the arc front; the basis for this belief is the appearance of Cb cells on the visible imagery, not the height measurements which suffer from the lower resolution of the infrared imagery.

3. Conventional Observations

Soundings taken every six hours at Dakar and Bamako indicate an environment typical of pre-squall conditions with convective instability and strong shear. The 1200 Dakar sounding (Fig. 6 a) has an inversion at 910-950 mb which capped a moist layer of light southerly monsoon winds, beneath dry continental easterlies extending up to a stable layer at 480 mb. At 2400 GMT after the passage of the "sister squall" the air was saturated above 850 mb and moist-adiabatic.

The θ_e index is useful to infer the source of air that has travelled through a storm. The vertical profile of θ_e at Dakar (Fig. 7) shows a minimum at 800 mb and a maximum at 900-1000 mb, evidence of convective instability at 1200 GMT. Through a process of overturning, the "sister" squall "homogenized" the air below 500 mb by midnight (2400 GMT). The profile at 1800, before the passage of the squall, reflects probable moistening of the mid-layers by several local storms.

The NCAR Queen Air penetrated the flank of the squall along the track on Fig. 1 b. At the point where the arc-cloud crosses this track, mission scientist E. J. Zipser noted a narrow zone of rain showers and gusts, and the absence of low cloud beneath an extensive anvil from which rain fell. The instruments recorded an intensification and shift of the wind from SE to E, a more gradual drop of 7° C. in dew-point over 40 km, then a gradual drop of 5° in temperature. After 120 km the craft climbed to take the sounding in Fig. 6 b, which shows a shallow, cool and moist stable layer capped by a warmer unsaturated layer above 930 mb with steady winds of some 30 knots (Environmental Data Service, 1976 c). This non-turbulent, unsaturated layer in a zone of steady rain is evidence for a mesoscale downdraft (Zipser, 1969, 1971).

4. The Relative Windfields

Previously the windfield near a squall line has been inferred by compositing soundings from one or more cases (Obasi, 1974, ASECNA, 1975; Houze, 1977). In this study windsets were generated by cloud-tracking at three levels on September 5, at 1200 and 1430 GMT (when the system was mature), with emphasis on tracking: a) the arc front; b) small cumulus marking the monsoon flow; c) mid-level cloud debris as evidence of jets at that level; and d) the cirrus outflow from the "anvil".

The windsets in the low, middle, and high layers were judged to best represent the 950, 700-600, and 250 mb levels respectively, by comparison with the soundings. The edited windsets at the three levels are plotted in Figures 8a, 9a, and 10a over the squall-line cloud outlines, with the streamlines and isotachs superimposed. The cloud outlines in Figs. 8 and 9 can be seen on the 1200 GMT image in Fig. 3, and those in Fig. 10 (a later windset) on the 1500 GMT image. The rawind reports are also plotted, and on the low-level chart (Fig. 8a) the surface and ship reports and <u>Queen Air</u> measurements as well. After performing a gridpoint analysis and subtracting the mean motion of the arc front (16 m/s from 84^{o}), each plot has been transformed into a streamflow analysis in a reference frame relative to the squall line (Figs. 8b, 9b, and 10b). These best indicate the inflow or outflow with respect to the leading edge of the squall in low and mid levels. It must be remembered that the Cb elements and the anvil cloud move more slowly than the leading edge.

In the low layers the west African monsoon converged from the south towards a confluence line that extends along the coast and westward from Dakar (Fig. 8a). In the relative-motion chart (Fig. 8b), the squall is seen to engulf this monsoon air.

Scattered patches of middle cloud ahead of the squall and a broad patch far to the east were tracked, but for lack of cloud tracers, the flanks and backside of the squall were not mapped. Nevertheless, the mid-level winds were deemed important enough to merit a careful attempt at mapping.

The mid-level tracers marched virtually in step with the arc front, so that it is difficult to determine whether there was relative inflow towards the front of the squall line at all levels. Most of them indeed move more slowly than the front, but a few were tracked at the same velocity. These may indicate a possible "steering level" wind, the momentum of which may be brought down to the gust front by the downdraft beneath the anvil. The same uncertainty exists for mid-level inflow from the rear; however, in comparing Figs. 9 and 10, there is no doubt that the westward current is fastest in the middle levels, so that it flows into the squall line system, towards and underneath the anvil, from the rear. The apparent outflow behind the system in Fig. 9b is misleading because the streamlines are extrapolated from the motion of the altostratus deck at the extreme right, and because the streamflow is plotted with respect to the arc front, not the slower-moving anvil, which itself would be displaced towards the right in Fig. 9b. The tangential component of the relative flow is easier to establish. When the imagery is animated in a storm-relative reference frame by keeping the arc front in the center of the field of view, a slight north or south motion of the clouds indicates their position with respect to a synoptic wave. On the normal mid-level plot (Fig. 9a) the squall is positioned in a trough of an easterly wave, but in Fig. 9b the cyclonic relative blow becomes evident especially ahead of the arc. The location of the squall-line disturbance is plotted in Fig. 11 in relation to the African wave categories analyzed by Payne and McGarry (1977) during phase III of GATE. The squall propagated faster than the wave until it overtook the trough at approximately 1200 GMT. After this the locus of intense squall-line activity marched westward with the wave trough, though individual arc fronts would run ahead at a faster clip and expire.

The high-level field (Fig. 10) consists of two regimes at different levels, southeasterlies over the anvil and easterlies downstream from the coastal-storm cirrus. Relative to the storm (Fig. 10b) the former sweep the "anvil" downstream (over the mid-level air entering from the rear) and accelerate as they traverse its breadth. The extension of the anvil towards the rear is common in tropical squalls but in marked contrast to many mid-latitude storms (Newton, 1967).

5. The Mass Budget

The vertical transport of mass within convective systems was first estimated from satellite imagery by Sikdar and Suomi (1971) by measuring the expansion of the anvil and applying a three-layer circulation model. Suchman _et al_. (1977) refined this model to estimate the mass inflow from low layers into cloud clusters and the mass outflow from the anvil. Windsets derived from tracking cumulus and cirrus were used to estimate the inflow and outflow respectively. The model only crudely estimates the depth of the layers and disregards the role of the mid-troposphere. A version of the model using the area-expansion technique was used to estimate the mass flow into the anvil and also in the mesoscale downdraft of the 5 September disturbance. The rapid computation of area within boundaries drawn on McIDAS images facilitated the two estimates.

The depth of the density-current outflow from thunderstorms has been estimated at 600 meters by GATE tethered balloons (Wylie, 1976) and at 1000 meters by instrumented towers (Goff, 1976). The mass outflow from the downdraft is arrived at by assuming these values as lower and upper bounds and measuring the rate of expansion of a boundary drawn around the mesoscale cold air pool on the images. The visible arc line clearly marks the expanding front of this area; a remarkably persistent cloud-free zone behind the squall system was judged to mark the extent of the pool to the rear. The eastern edge of this clear zone at 1300 GMT (Fig. 3) was selected as the rear boundary, which was kept fixed. Using mass continuity, the mass descent is given in Table 1 for three periods when the arc front expanded at different rates. At maturity, the downdraft transported some 5×10^9 kg/s, and even more during the decay stage.

To estimate the mass entering the anvil from the updrafts of the Cb cells, the depth of the high-layer outflow is assumed to lie between one km (from Sikdar and Suomi, 1971) and 3.2 km (from Suchman et al., 1977). By measuring the expansion of the anvil area above an infrared brightness threshold corresponding to 200 mb, and employing mass continuity, the upward transport is as shown in Table 1. The result, some 10^{10} kg/s, is one order of magnitude greater than a typical large thunderstorm in mid-latitudes, and about twice the value (from 2 to 6 x 10^{9} kg/s) obtained for one active GATE cloud cluster (Suchman et al., 1977). The result underestimates the real upward transport because the anvil depth observed in other squalls (Houze, 1977) exceeds the conservative assumption here, and because the outer edge of the cirrus shield evaporates as it expands.

The growth of the anvil and of the surface outflow are plotted in Fig. 4. Suchman et al. (1977) found that the maximum ascent in the upper troposphere lags the maximum ascent from the boundary layer by 3 to 6 hours. In the squall, upper-level ascent steadily increases and then declines over several hours, while the downdraft requires time to become established but then is still spreading three hours after the time of peak ascent. During the vigorous phase from 0800 to 1130, the mass descent is about one-fourth of the mass ascent; at maturity the magnitude of the two circulations are comparable.

6. Conclusions

Before the satellite era, the African "disturbance line" was known to be a squall line of great dimension, a set of storms sharing a common raining anvil and a pool of rain-cooled air (Fortune, 1977). It marched westward along the boundary between the African monsoon and the mid-level easterlies, from 100 to 1000 km south of the surface trace of the intertropical front, and was believed to be driven by the release of potential energy at this boundary. Some advanced an association with easterly waves, mid-level jets, or low-level convergence zones. Satellite images demonstrated a characteristic appearance of the lines, and indicated that their occurrence was tied to geographical, diurnal, and synoptic-wave factors, as well as confirming their grand size and rapid propagation.

With a leading edge marked by intense showers and a gust front driven by the outflow from rain-cooled downdrafts, an African squall resembles those in mid-latitudes. Both also thrive on the vertical shear and convective instability at the boundary of two markedly different air masses (Newton, 1967). The African variety, however, persists for days rather than hours, affects a more extensive area, propagates westward, and forms an anvil cloud behind, not in front of, the active cells, the result of a profile of westerly shear above a mid-level wind maximum.

The squall on 5 September 1974 was typical of those analyzed in composited studies (ASECNA, 1975; Aspliden et al., 1967; Miller and Betts, 1977; Obasi, 1974) in its long lifetime, areal extent, speed and direction of propagation, and thermodynamic modification of all levels of the troposphere. It was also typical in that the component squall systems evolved unsteadily and irregularly, except the arc fronts marched at a rather steady rate (Fig. 2). Unlike most squalls, the disturbance developed vigorously during the morning hours (of 5 September) and originated behind a wave trough. It shares features of squalls observed on 1 April 1967 (Zipser, 1969), on 5 September 1974 in the GATE area (Houze, 1977), and at other times during GATE. The similarities include the discrete propagation of new Cb elements or squall lines that form well ahead of the old arc front; a spatial pattern consisting (from front to rear) of an arc front, discrete storm cells, anvil cloud, and a broad zone of subsidence in each squall system; the displacement of highest cloud tops well back of the low-level squall front; and enhanced convection at the junction of the front and other convective cloud lines.

A conception of an African squall which emerges from this study is depicted in Fig. 12. The top figure depicts the airflow relative to the ground; the lower figure, the airflow relative to the cloud elements. Satellite imagery shows the gust front (B) marked by a roll cloud (C) marching at some 20 m/s at the leading edge of the disturbance. Storms develop in discrete towers (D), eventually to the tropopause. They are visible as pinpoint Cb elements which acquire westward momentum from the mid-level current as they grow, until their tops are fused into an extensive "anvil" (F) from which moderate rain falls. The rain cools a layer of dry air entering from the rear, which forms the mesoscale downdraft (G). Sinking to near the surface this spreads out and maintains the momentum of the gust front. In the relative-motion diagram the squall front advances faster than the jet (pressure forces in a mesohigh can accomplish this). The front eventually outpaces the anvil and expires; then another front may initiate a new squall-line further back. Thus a succession of lines can occur in a disturbance lasting many days.

The satellite analysis of this case contributes these points to the above conception:

a) A squall system in evolution is characteristically indicated by the appearance of an arc line, discrete Cb cells, and an anvil on the imagery. As the system develops and decays over 6 to 12 hours, the arc tends to run well ahead of the anvil, which expands and then fades while the downdraft is expanding over a broader area.

b) An African disturbance line is a longer-lived subsynoptic phenomenon encompassing one or more squall systems that evolve as neighbors or successors of each other. New squalls can form in advance of the leading edge of old systems as well as in their midst. The disturbance may propagate faster than the typical African wave, although the most vigorous development occurs on overtaking a wave trough.

c) The cyclonic flow in mid-levels about the system, the divergent outflow at cirrus level, the expanding area at the surface behind the arc front, and the change in the θ_e profiles all suggest that a sub-synoptic circulation is set up, consisting of convergence at mid-levels into an organized downdraft and outflow at the surface. At the gust front this mesoscale current forcibly lifts subcloud air into an ensemble of convective towers, where after some entrainment of mid-level air, further ascent and essentially all outflow occur in a thick massive anvil.

d) The mass transports into the anvil and into the organized downdraft are comparable and of the same magnitude as in tropical cloud clusters covering larger areas. Squall lines then are significant contributors to the energetics of the tropics.

Questions still remain about the structure and dynamics of African squalls; among the foremost of them are:

-- Is the subsynoptic circulation which was associated with the 5 September disturbance created by the squall-line system itself? Once established, the propagating mid-level convergence may spawn new squall lines after the older ones expire, as in this case.

-- Does a disturbance line propagate faster than the wind at all levels in the troposphere, so that mid-level air enters the system from the forward side, either to be entrained in the updrafts or to pass around them into the organized downdraft

(Miller and Betts, 1977)? Or as in this case, might there be a "steering level" wind with a velocity equal to the arc front?

-- A key element in the subsynoptic circulation is the direct transfer of momentum from a mid-level "jet" to the surface. As the jet "bevels" its way from desert into monsoon air, can a Saharan "haboob" be transformed into a disturbance line? Danielsen (1974) has noted a similar transformation in the American Southwest.

-- Does ascent occur in vertical or tilted currents within the individual Cb elements, or in a mesoscale updraft within the anvil as well? Such a current is predicted in Brown's (1974) model and strongly suggested in Houze's (1977) case.

-- Are variations in the intensity, velocity, and precipitation of squall-lines (ASECNA, 1975) tied to local geography or to synoptic low-level convergence as well as to the synoptic waves? No such links were seen in this case.

-- What causes the squall lines to evolve so differently from the more innocuous convective cloud bands in the tropics? Both have been observed during GATE to exist in the same environment.

The data base from GATE is supporting the extension of tropical squall-line models by Houze (1977) and E. J. Zipser (at the National Center for Atmospheric Research) and compositing studies by C. I. Aspliden and Y. Tourre (University of Virginia) which are expected to answer these questions. For the future, it is suggested that the First GARP Global Experiment investigate convective systems of both the cloud cluster and squall line varieties by combining time-lapse satellite imagery with a modest improvement in the African surface network and organized sampling of the disturbances.

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REFERENCES

ASECNA (1973), "Operation Niger - ASECNA," 12-23 Juillet 1972. Bureau d'Etudes, Agence pour la Securite de la Navigation Aerienne (ASECNA), B. P. 3144, Dakar, Senegal.

ASECNA (1974), "Operation Pre-GATE ASECNA," 1-10 Aout 1973. Bureau d'Etudes, ASECNA, Dakar, Senegal.

ASECNA (1975), "Operation Pre-GATE ASECNA, Complements d'Analyse," 1-10 Aout 1973. Bureau d'Etudes, ASECNA, Dakar, Senegal.

Aspliden, Carl I., Yves Tourre, and John B. Sabine, (1976), "Some Climatological Aspects of West African Disturbance Lines During GATE," Monthly Weather Review 104, #11 (Aug. 1976) pp. 1029-1035.

Brown, J. M., (1974) "Mesoscale motions induced by cumulus convection: a numerical study." Ph.D. thesis, Dept. of Meteorology, Massachusetts Institute of Technology, Cambridge, Mass., 206 pp.

Danielsen, E., (1974) "The Relationship between Severe Weather, Major Dust Storms and Rapid Large-Scale Cyclogenesis," notes from a colloquium: Subsynoptic Extratropical Weather Systems, N.C.A.R., summer 1974, pp. 215-241.

Dhonneur, Georges (1970), "Essai de Synthese sur Les Lignes de grains en Afrique Occidentale et Centrale," Publication #20, Direction d'Exploitation Meteorologique, ASECNA, Dakar, Senegal.

Eldridge, R.H. (1957), "A Synoptic Study of West African Disturbance Lines," Quart. J. Roy. Meteor. Soc., 83, #357, July 1957, pp. 303-314.

Environmental Data Service (1976), (a) Microfilm charts of the surface and upper-air flow in Phase III of GATE. (b) GATE Quick-Look Data set, on computer tape. (c) Microfilm records of aircraft missions during Phase III of GATE. Available from World Data Center A, National Climatic Center, Asheville, N.C.

Fortune, Michael (1977), "The West African Squall Line -- a Meteorological History," a report available from the Space Science and Engineering Center, University of Wisconsin, Madison, Wisc.; and "The West African Squall Line -- a Satellite Perspective of a Tropical Tempest," M.S. Thesis, University of Wisconsin, 1977.

Goff, R. Craig (1976), "Vertical Structure of Thunderstorms Outflows," Mon. Weather Rev., 104, #11 pp. 1429-1440, Dec. 1976.

Gurka, James (1976), "Satellite and Surface Observations of Strong Wind Zones Accompanying Thunderstorms," Mon. Weather Rev., 104, #12, pp. 1484-1493.

Hamilton, R.A., and J.W. Archbold (1945), "Meteorology of Nigeria and Adjacent Territory," Quart. J. Roy. Meteor. Soc., 71, #309, pp. 231-264.

Houze, Robert A., Jr., (1977), "Structure and Dynamics of a Tropical Squall-Line System Observed during GATE," submitted to Mon. Weather Rev.

Latrasse, J. (1972), "Photographies Prises par Satellites -- Elements d'Application a la Meteorologie Tropicale," publication #22 of the Direction de l'Exploitation Meteorologique, ASECNA, Dakar, Senegal.

Lilly, Douglas K., editor (1977), Planning Documentation Volume, the Severe Environmental Storms and Mesoscale Experiment (Project SESAME), N.O.A.A. Environmental Research Laboratories, Boulder, Colo.

Miller, M. J., and A. K. Betts (1977), "Travelling Convective Storms over Venezuela," to appear in Mon. Weather Rev., 105, July 1977.

Newton, Chester W. (1967), "Severe Convective Storms," in Adv. in Geophysics, Vol. 12, pp. 257-308, Academic Press, New York.

Obasi, G.O.P. (1974), "Some Statistics Concerning the Disturbance Lines of West Africa," Symposium on Tropical Meteorology, Nairobi, Kenya, 1974, publ. by Amer. Meteorol. Soc., Boston, MA.

Payne, Steven and Mary McGarry (1977), "The Relationship of Satellite Inferred Convective Activity to Easterly Waves over Western Equatorial Africa and the Adjacent Ocean During Phase 3 of GATE," Mon. Weather Rev., 105, pp. 413-420.

Purdom, J.F.W. (1973), "Meso-highs and Satellite Imagery," Mon. Weather Rev., 101, (1973), pp. 180-181.

Sikdar, D.N., V.E. Suomi, and C.E. Anderson (1970), "Convective Transport of Mass and Energy in Severe Storms over the United States - an Estimate from a Geostationary Altitude," Tellus, 22, pp. 522-531.

Smith, E.A. (1975), "The McIDAS System," IEEE Transactions on Geoscience Electronics, GE-13, pp. 123-136.

Suchman, David and David W. Martin (1976), "Wind Sets from SMS Images: An Assessment of Quality for GATE," J. Applied Meteor., 15, #12, pp. 1265-1278.

Suchman, David, David Martin and D.N. Sikdar (1977), "Deep Convective Mass Transports - Two Estimates from Geostationary Satellites," forthcoming in Mon. Weather Rev., 105, August 1977.

Wylie, Donald P. (1976), "Tropical Observations of Mixed Layer Changes Caused by Cumulus Downdrafts in the Gate Program," Ph.D. Thesis, Univ. of Wisconsin.

Zipser, E.J. (1969), "The Role of Organized Unsaturated Convective Downdrafts in the Structure and Rapid Decay of an Equatorial Disturbance," J. Applied Meteor., 8, pp. 799-814, October 1969.

Zipser, E.J. (1971), "A Comparison of Oceanic and Continental Squall Lines in the Tropics," N.C.A.R. Preprint, Boulder, Colo.

FIGURE CAPTIONS

Figure 1(a). Visible SMS image of the squall within two hours of its origin, at 1500 GMT, 4 September 1974. Both Figures 1(a) and 1(b) appear on the same scale.

Figure 1(b). Full resolution (1 km) visible image of the squall at 1300 GMT 5 September 1974. Dakar is at upper left, on the peninsula of the coastline. The track flown by the Queen Air is shown by the diagonal line. A 2° grid of latitude and longitude is superimposed.

Figure 2. The advance of the squall front. From right to left, the solid curves indicate the advancing edge of the cloud mass on the infrared images, from time of origin until 1000 GMT 5 September. After 1000 GMT, the thicker dashed lines indicate the location of the arc front on the visible images; the dotted lines, the remnants of the front. The solid lines at the upper left indicate the forward edge of a northern squall born at 1400 on 5 September. The map extends 2000 km from the Atlantic Coast (left) to Timbuktu (right).

Figure 3. This montage of visible SMS images depicts the organization and decay of the squall line system from 800 until 1600 GMT on 5 September 1974 over west Africa (as plotted in figure 2). A 2° grid of latitude/longitude is overlaid. The images have been displaced so that a vertical line intercepts the 14th parallel at the same longitude on all images.

Figure 4. The area under the influence of the downdraft (a), the area covered by the "anvil" at heights greater than 200 mb (b) on the infrared images, for the main squall, and the area similarly covered by the anvil of the "sister" squall (c), on 5 September 1974.

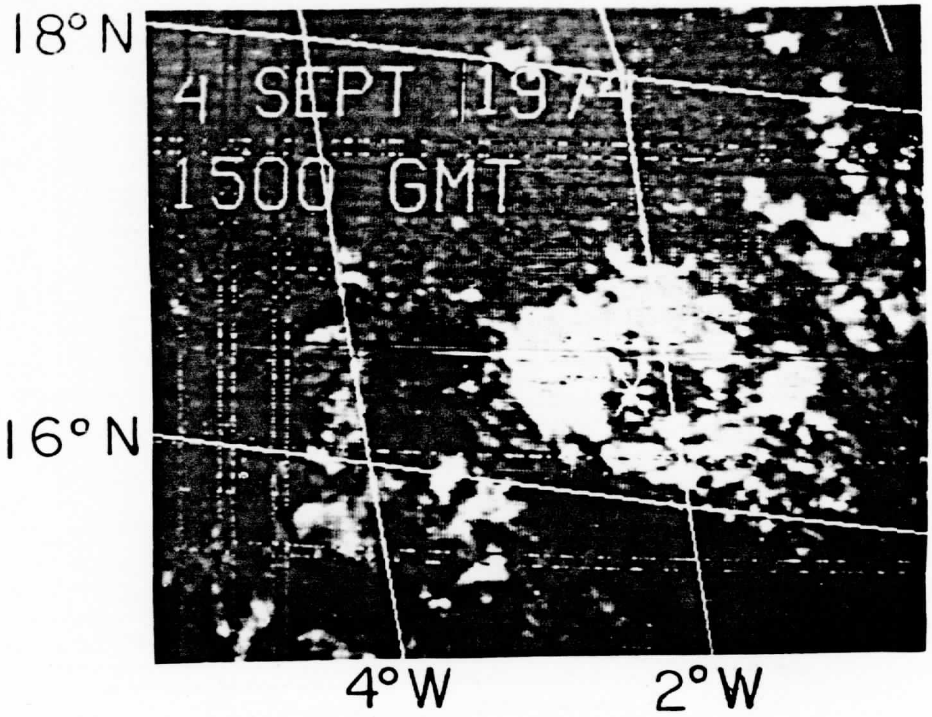
Figure 5	The initial evolution of the northern "sister" squall on 5 September 1974, in a cross section through the cloud mass. Times are in GMT. The dots indicate sampling points where height and thickness were measured on McIDAS images.
Figure 6	(a) Radiosoundings at Dakar on 5 September 1974, at 1200 (left) and 2400 (right). The wind barbs indicate speed in knots. (b) Sounding from the _Queen Air_ flight 150 km behind the squall front, underneath the anvil. At left, the windspeed (in knots) was measured only up to 840 mb. A cool, moist stable layer of light winds lies beneath 930 mb; above is a warm unsaturated layer of strong outflow.
Figure 7	The vertical profile of equivalent potential temperature θ_e at Dakar at 1200 (solid), 1800 (dotted), and 2400 (dashed) on 5 September 1974. The pronounced vertical changes in θ_e were eliminated by the storm 12 hours later.
Figure 8	Low level windfield at 1200 GMT. The heavy dark line outlines the arc front and anvil; the dotted line at left, the coast of Africa. (a) Above, original wind vectors streamlines, and isotachs (dashed) at 2 m/s intervals. Superimposed are surface and ship reports (open circles) and _Queen Air_ reports (triangles). (b) Below, low level flow relative to the arc front.
Figure 9	Mid level windfield at 1200 GMT. (a) Above, original winds, rawind reports for 700 mb (open circles), streamlines, and isotachs at 2 m/s intervals. (b) Below, mid level flow relative to the arc front.
Figure 10	High level windfield at 1430 GMT. (a) Above, original winds, rawind reports at 250 mb for 1200 (open circles), streamlines, and isotachs at 2 m/s intervals. (b) Below, high level flow relative to the arc front.

Figure 11 Position of 700 mb wave trough (dashed) to the squall line cloud image (stippled) on Sept. 5. The streamlines and wind barbs represent filtered winds at 700 mb as analyzed by S. Payne *et al* (1977).

Figure 12. A conception of an African squall line in cross section. Above, main features and flow with respect to the ground. Below, flow relative to the cloud elements. The main features are: A: Boundary or inversion between the monsoon and the easterlies. B: The gust front. C: The roll cloud. D: Developing Cb towers. E: Heavy rainshowers. F: The anvil cloud. G: The mesoscale downdraft.

AIRSTREAMS:

1. Monsoon, calm or light southerlies
2. African Easterly Jet
3. High level easterlies
4. Surface outflow, cold density current from the downdraft
5. Numerous convective updrafts
6. Air being entrained in the updrafts from all sides
7. Organized mesoscale downdraft
8. Subsidence in the wake of the storm


18° N
4 SEPT 1974
1500 GMT
16° N
4° W
2° W

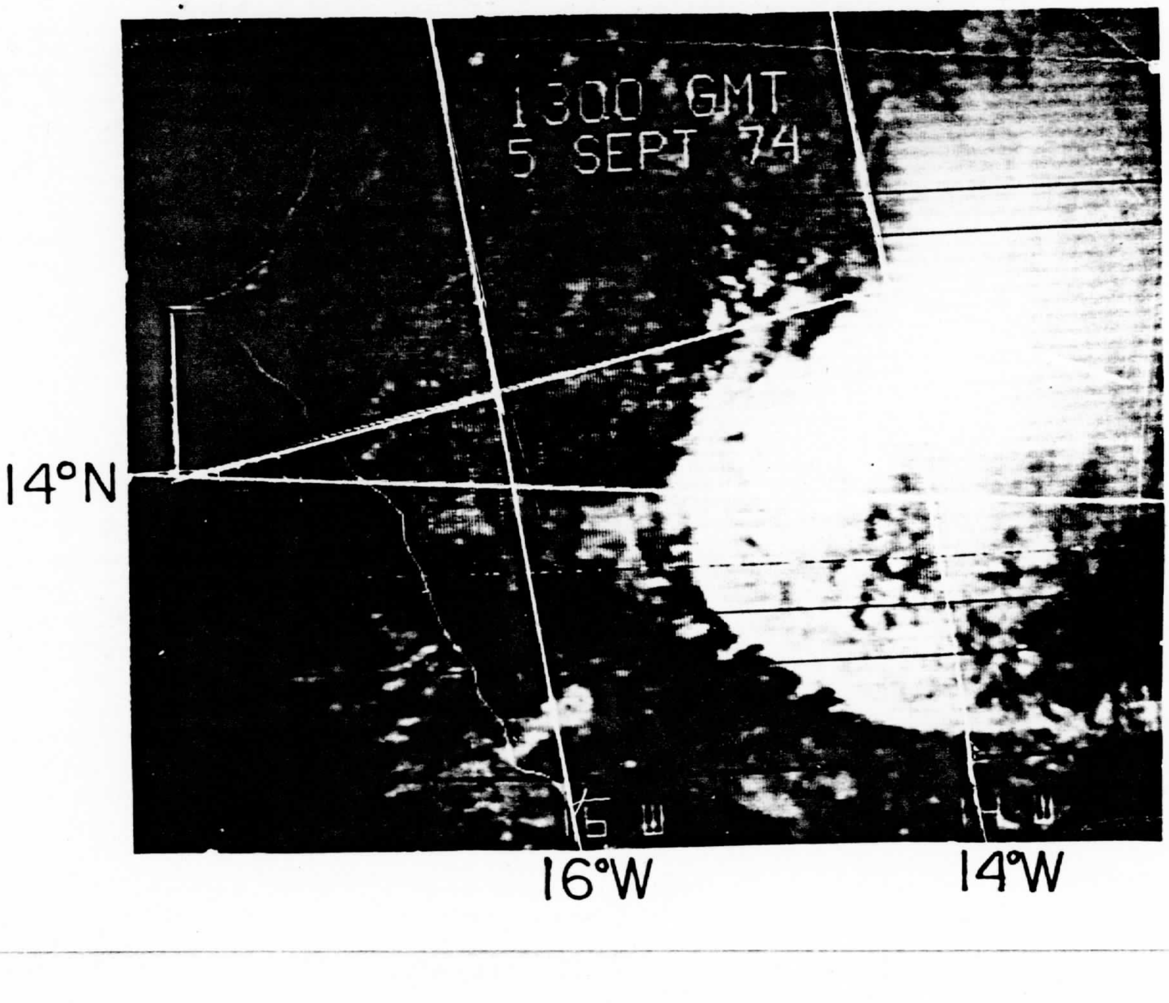
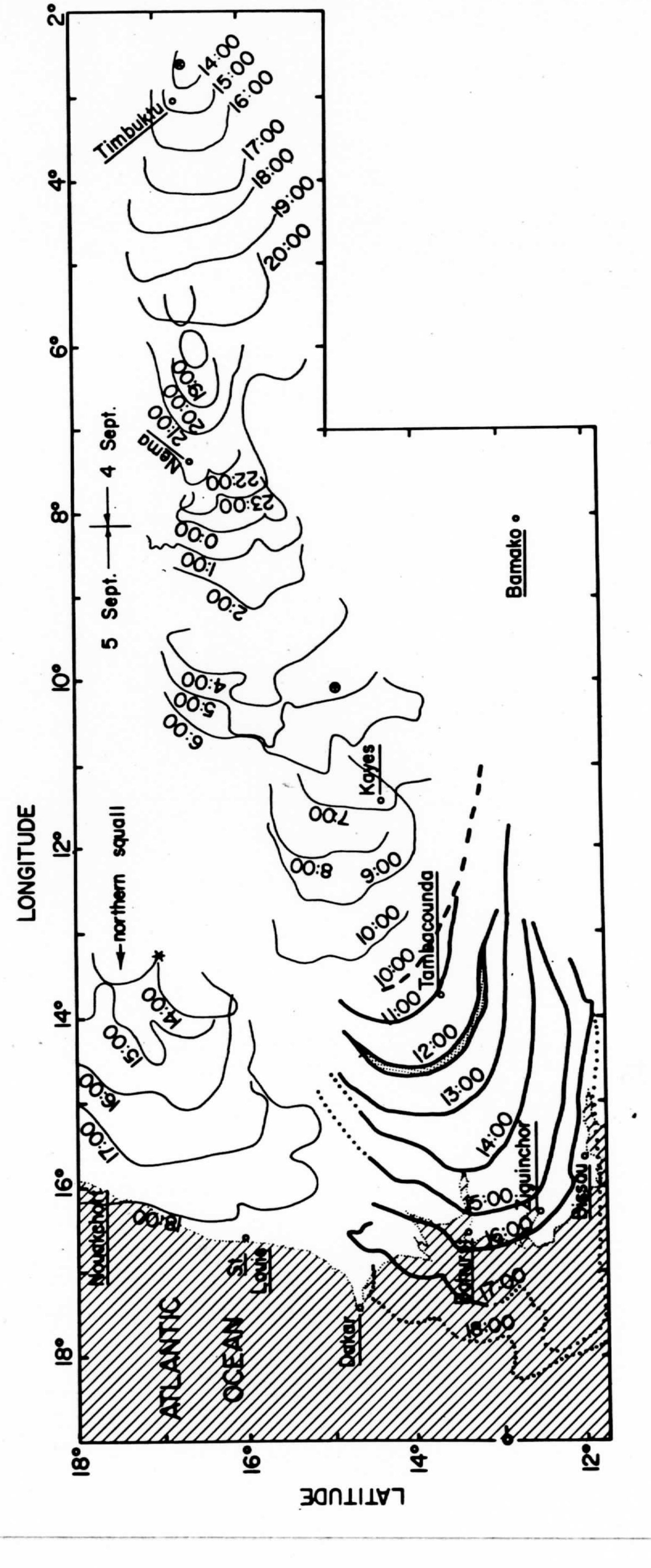

1300 GMT
5 SEPT 74
14°N
16 W
14 W
16°W
14°W

Fig. 2


LONGITUDE
LATITUDE
2°
4°
6°
8°
10°
12°
14°
16°
18°
Timbuktu
Nema
Bamako
Kayes
Tambacounda
Ziguinchor
Bissau
Banjul
Dakar
St. Louis
Nouakchott
ATLANTIC
OCEAN
5 Sept.
4 Sept.
northern squall
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
0:00
1:00
2:00
4:00
5:00
6:00
7:00
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9:00
10:00
11:00
12:00
13:00

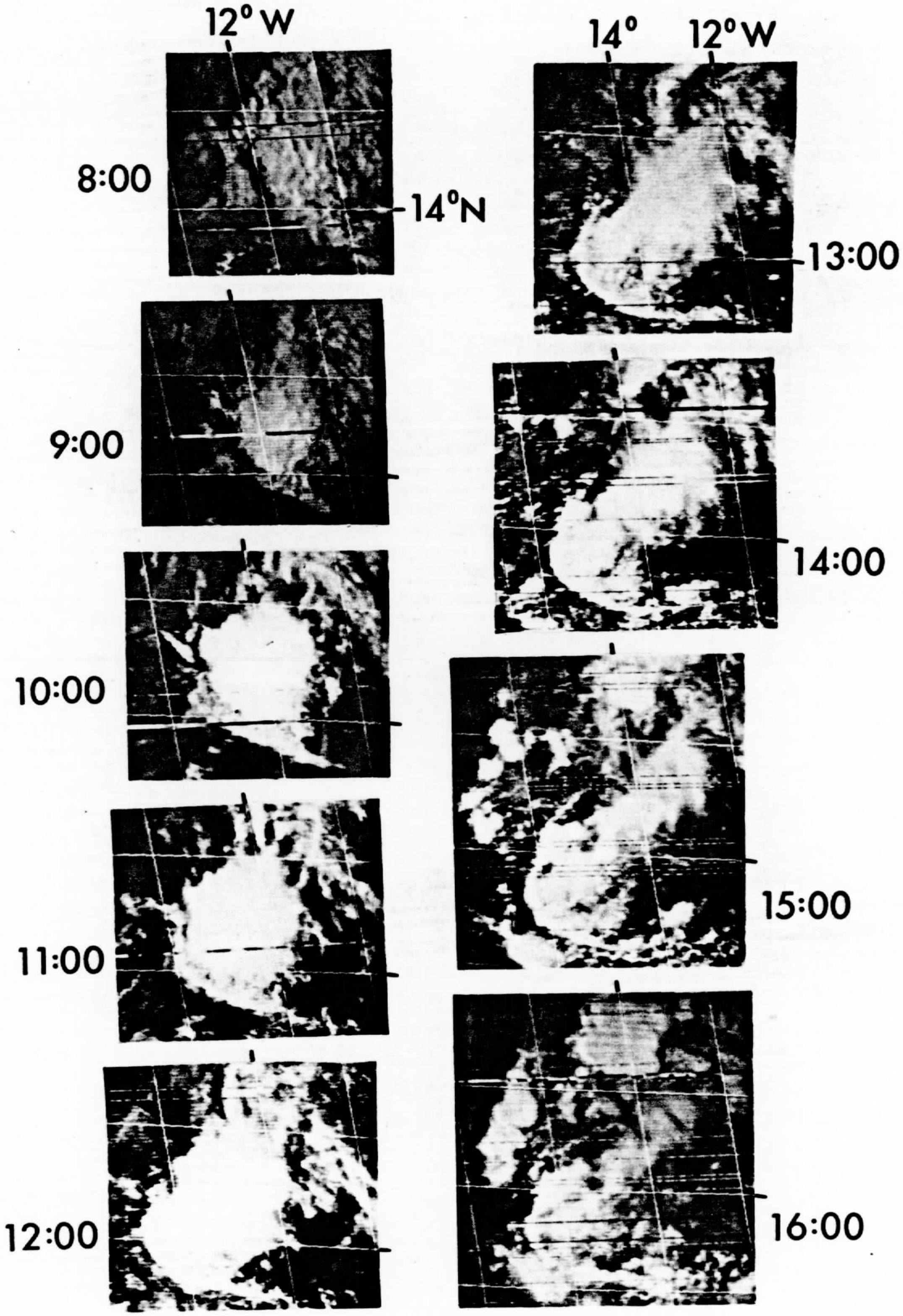
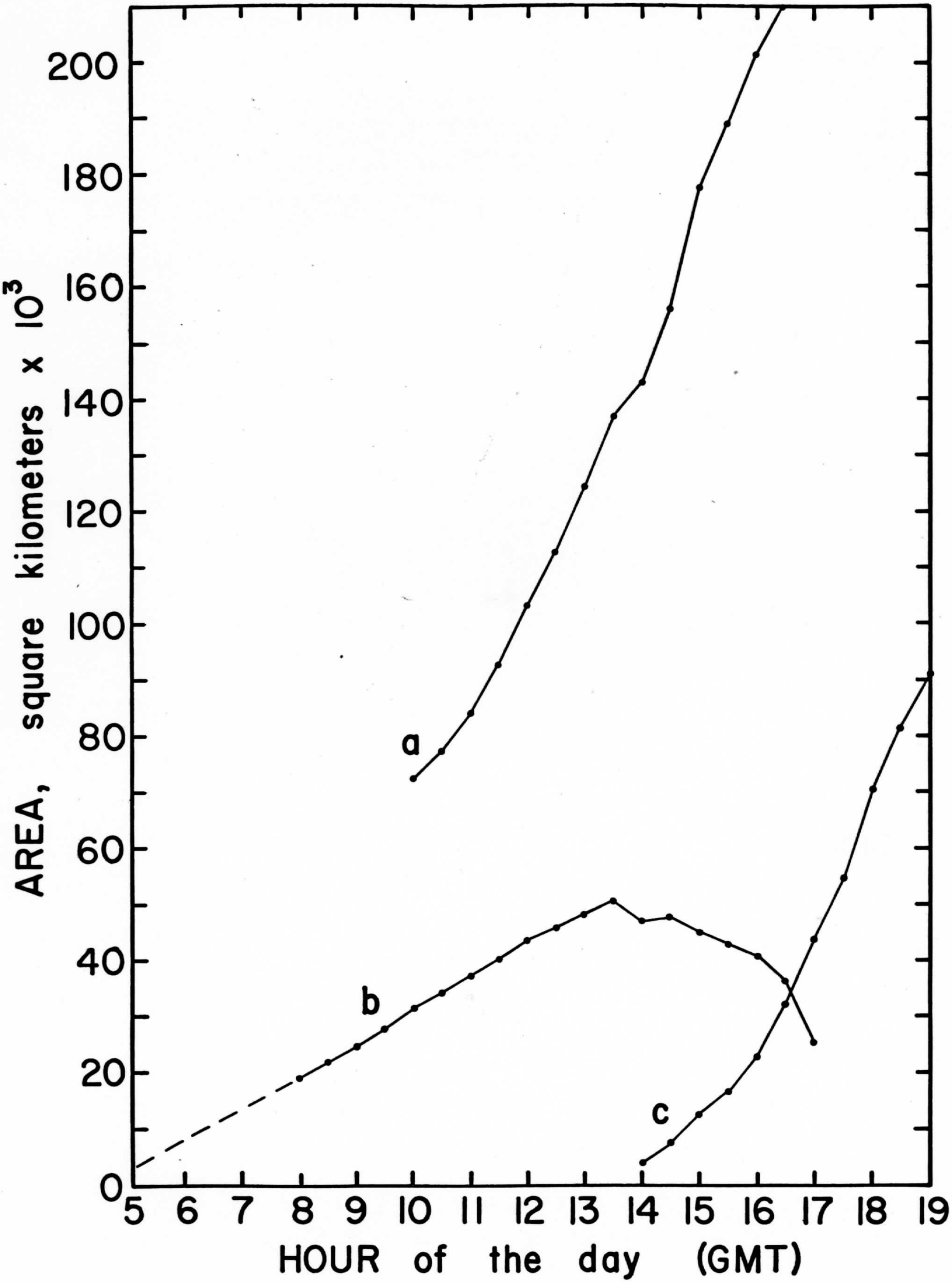


FIG. 3

Fig. 4



AREA, square kilometers x 10^3
0
20
40
60
80
100
120
140
160
180
200
a
b
c
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
HOUR of the day (GMT)

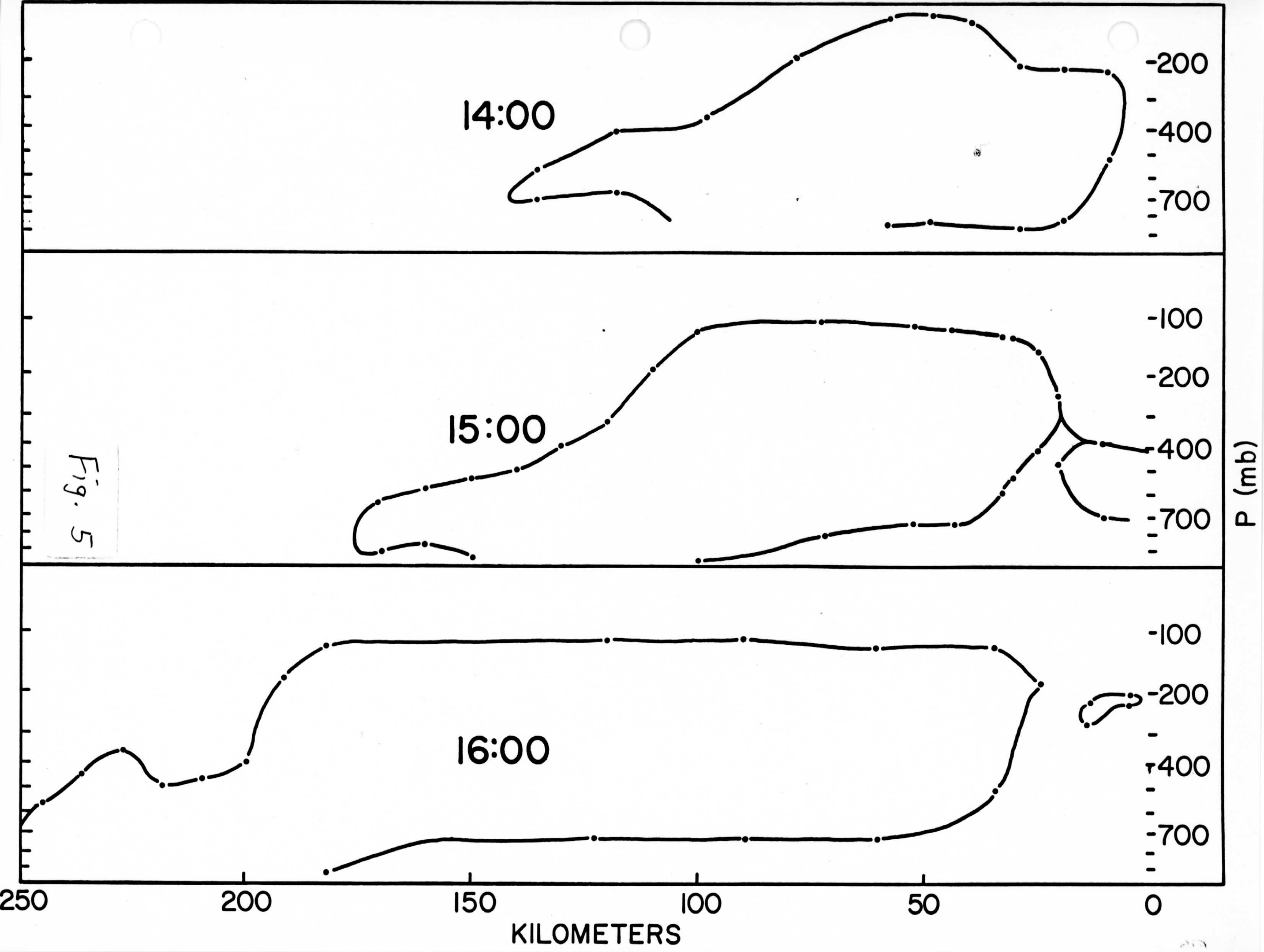

14:00
15:00
16:00
-100
-200
-400
-700
P (mb)
0
50
100
150
200
250
KILOMETERS

Fig. 5

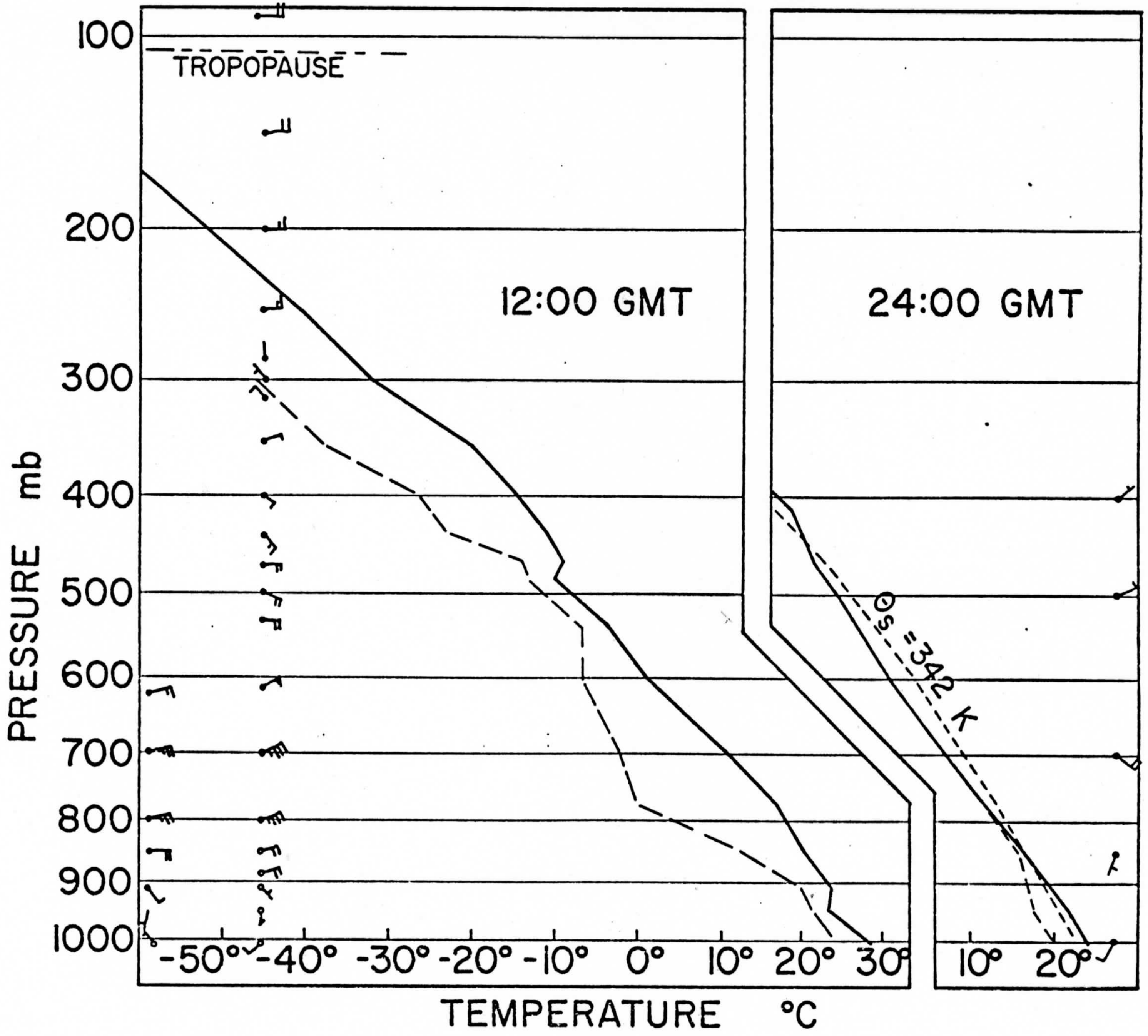

PRESSURE mb
100
200
300
400
500
600
700
800
900
1000
TROPOPAUSE
12:00 GMT
24:00 GMT
$\Theta_s = 342$ K
-50°
-40°
-30°
-20°
-10°
0°
10°
20°
30°
10°
20°
TEMPERATURE °C

Fig. 6(a)

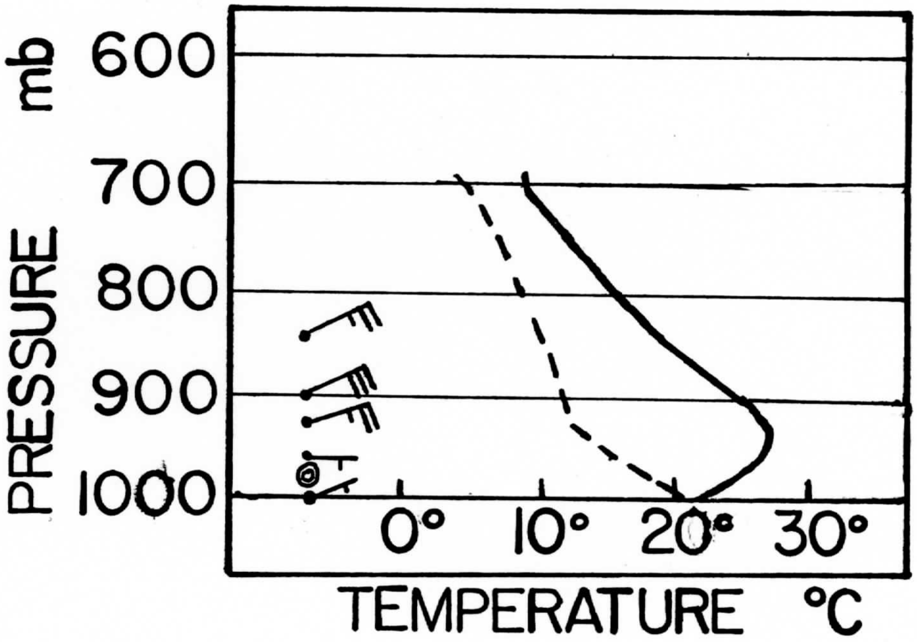


Fig. 6 (b)

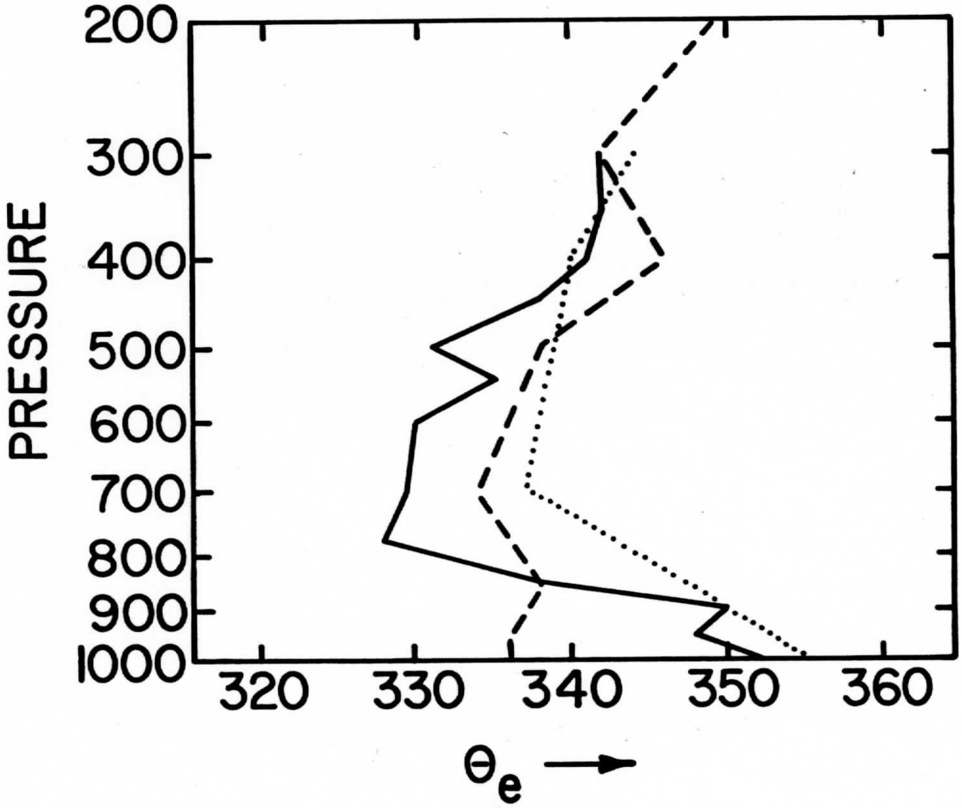
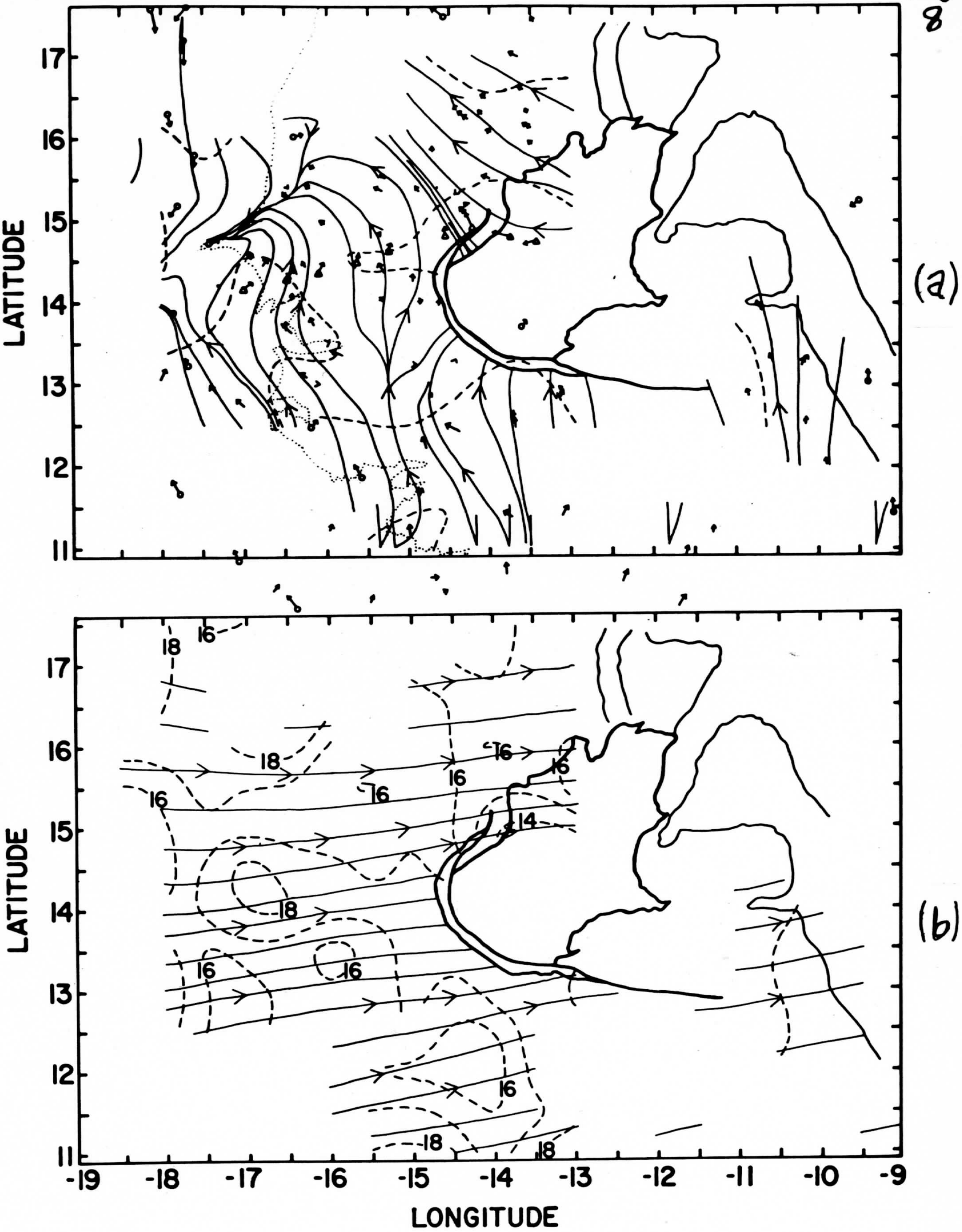

PRESSURE
200
300
400
500
600
700
800
900
1000
320
330
340
350
360
θ_e →

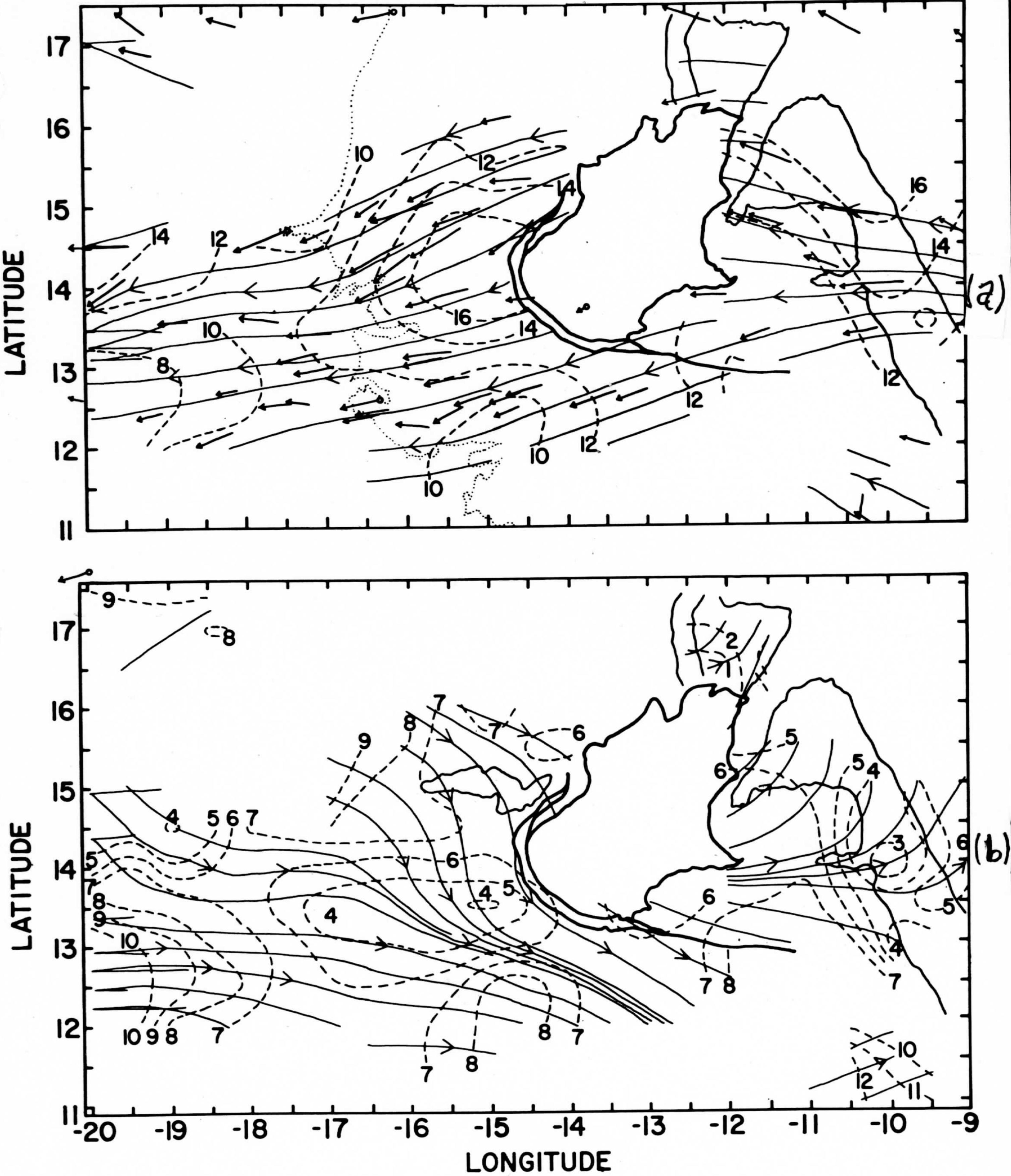
Fig. 7

Fig. 8



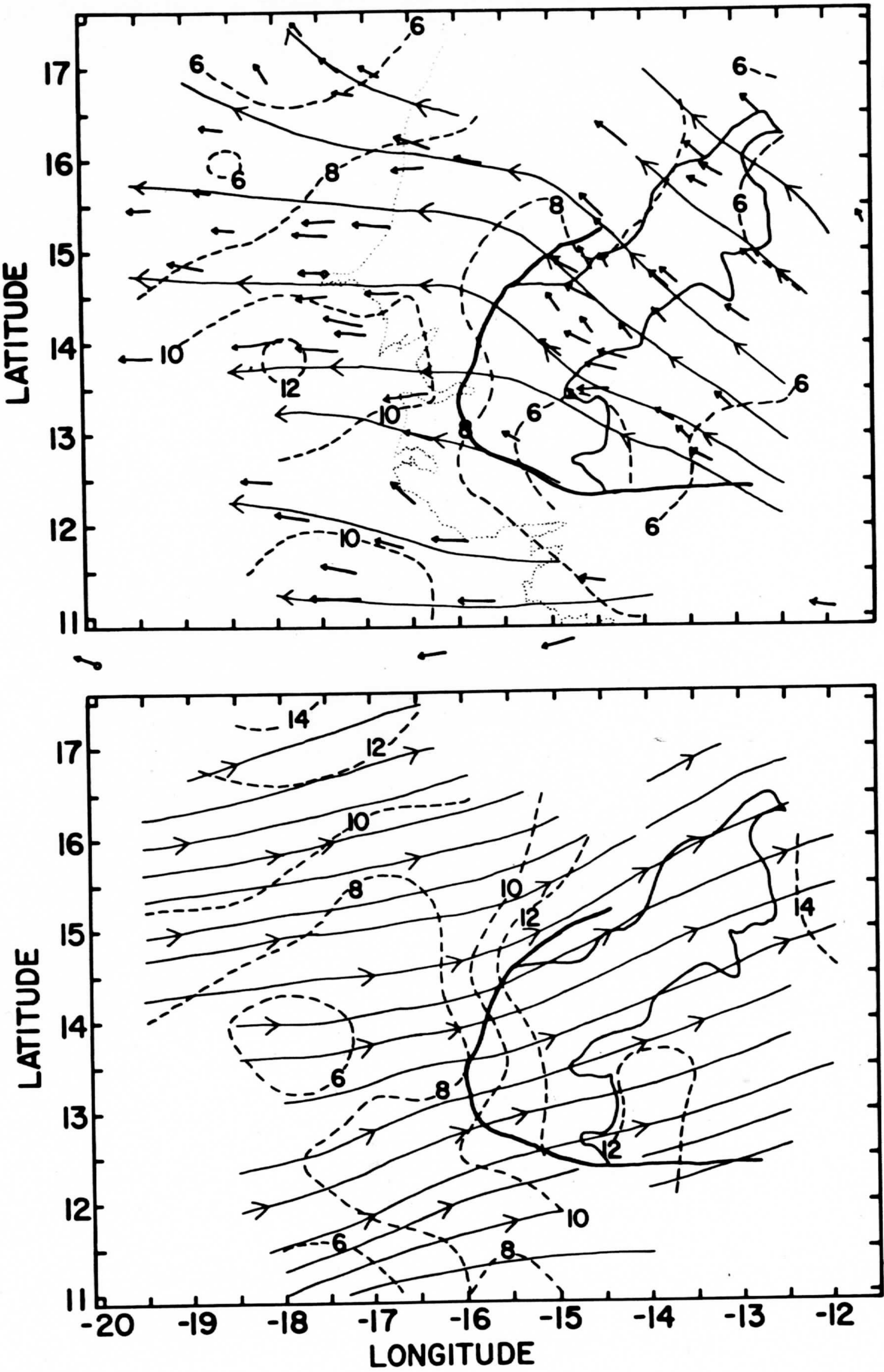
(a)
(b)
LATITUDE
LATITUDE
17
16
15
14
13
12
11
LONGITUDE
-19
-18
-17
-16
-15
-14
-13
-12
-11
-10
-9
16
18
18
16
16
16
16
16
14
18
16
16
16
18
18

Fig. 9



LATITUDE
17
16
15
14
13
12
11
10
12
14
16
14
12
10
8
12
12
10
10
16
14
12
(a)
LATITUDE
17
16
15
14
13
12
11
9
8
2
1
7
8
7
6
9
5
6
5
4
4
5
6
7
6
4
5
5
7
8
9
10
4
3
6
6
5
4
7
8
10
9
8
7
8
7
7
8
7
10
12
11
(b)
-20
-19
-18
-17
-16
-15
-14
-13
-12
-11
-10
-9
LONGITUDE

Fig. 10


(a)
(b)
LATITUDE
LONGITUDE
11
12
13
14
15
16
17
-20
-19
-18
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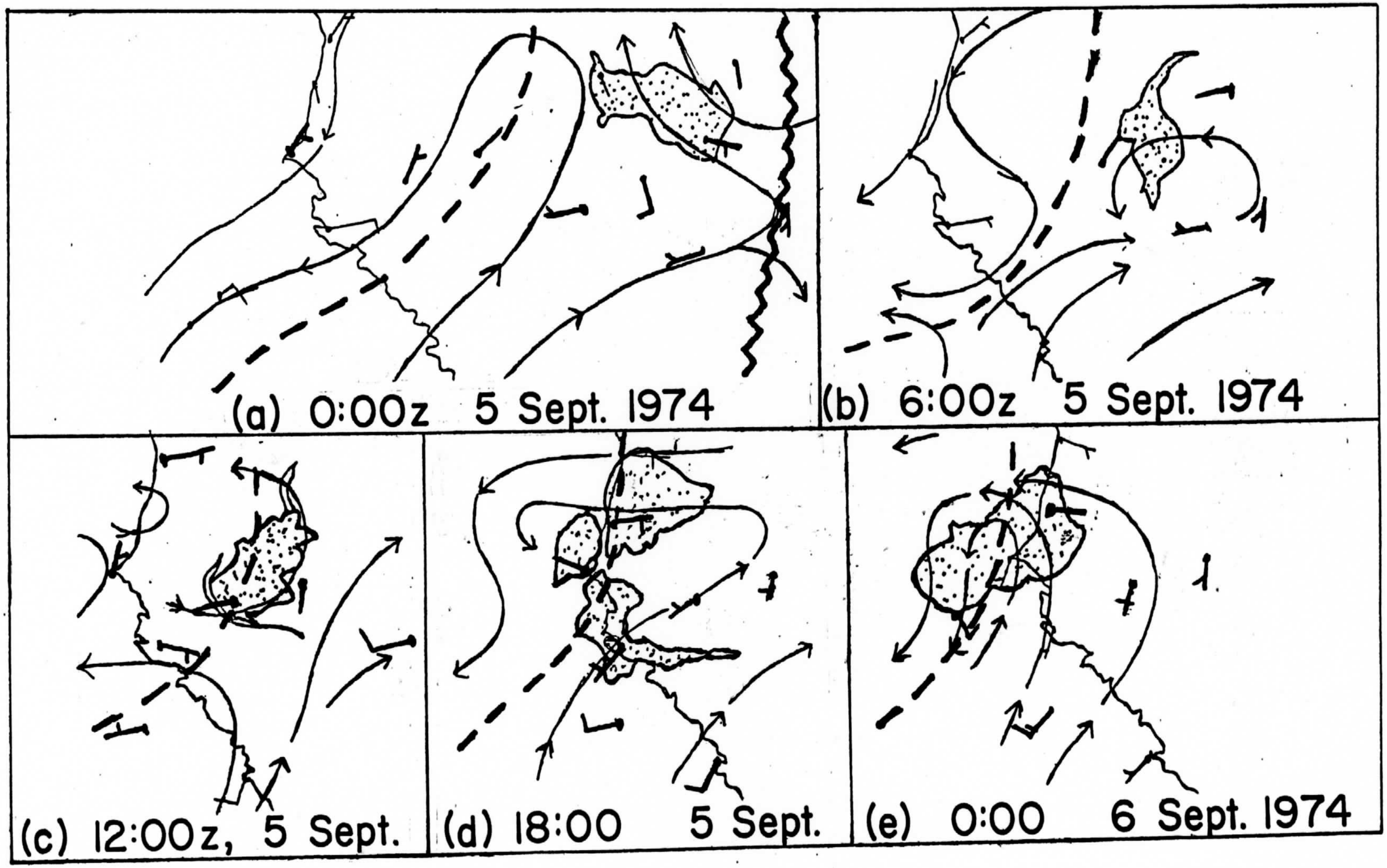
-16
-15
-14
-13
-12
6
8
10
12
14



(a) 0:00z 5 Sept. 1974

(b) 6:00z 5 Sept. 1974

(c) 12:00z, 5 Sept.

(d) 18:00 5 Sept.

(e) 0:00 6 Sept. 1974

Fig. 11

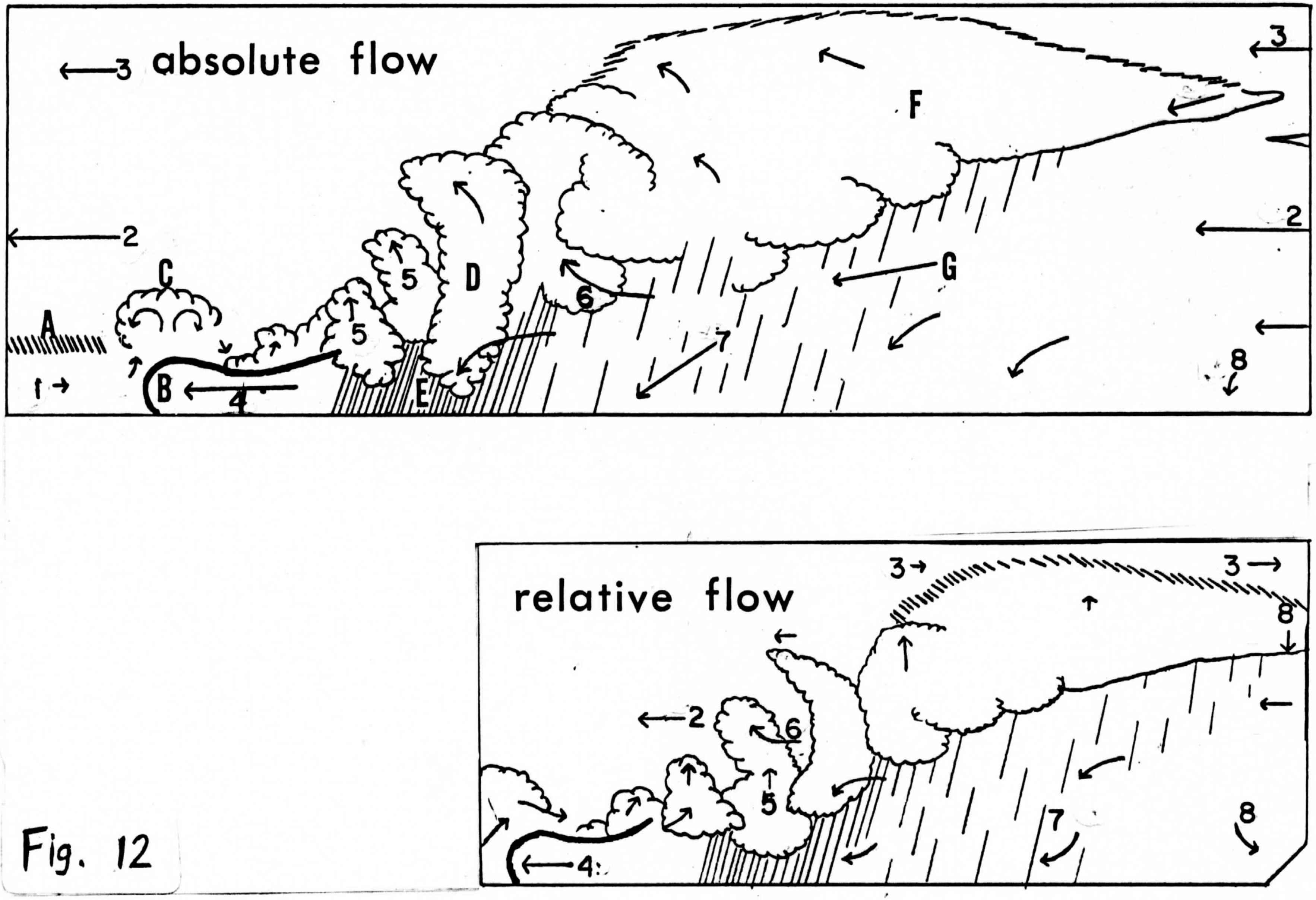

absolute flow
3
2
A
1
B
C
4
5
5
D
E
6
7
F
G
2
3
8
relative flow
3
3
8
2
6
5
4
7
8

Fig. 12

TABLE I

MASS TRANSPORT IN THE 5 SEPTEMBER SQUALL

in billion (10^9) kg/s

Hour, GMT:	before 1130	1130 - 1400	1400 - 1600
DESCENT in mesoscale downdraft	1.4 to 2.3	4.1 to 6.9	5.6 to 9.3
ASCENT into expanding anvil	3.8 to 11.	2.2 to 6.6	--