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COMPARISON OF AN OKLAHOMA SQUALL LINE TO MESOSCALE CONVECTIVE SYSTEMS IN THE TROPICS

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1. INTRODUCTION

Field experiments in the tropics, especially the Global Atmospheric Research Program's Atlantic Tropical and Monsoon Experiments (GATE and MONEX), have established the existence of mesoscale organization in the air motions and precipitation fields of tropical convective cloud systems [see review articles by Houze (1981) and Houze and Betts (1981)]. Observations of tropical squall-line systems generally depict a leading line of deep convective cells trailed by an area of stratiform precipitation that falls from a mid- to upper-level cloud layer emanating from the convective cells (Fig. 1). The cellular convective elements result from non-hydrostatic, buoyant vertical motions supported by low-level convergence. In contrast, the mid- to upper-level cloud shield and stratiform precipitation are accompanied by mid-level convergence and hydrostatic, mesoscale rising motion in cloud, with a mesoscale downdraft below cloud. Zipser (1969, 1977) distinguished the mesoscale downdraft from the convective-scale downdrafts at the leading edge of the system. Numerical experiments carried out by Brown (1979) identified cooling by evaporation of falling precipitation as an important mechanism sustaining the mesoscale downdraft. Radar reflectivity measurements in GATE revealed a marked bright band at the melting level as a characteristic feature of the stratiform precipitation falling through the mesoscale downdraft (Houze, 1975, 1977; Shupiatsky et al., 1975, 1976), and Leary and Houze (1979) showed that the melting contributes along with evaporation to the cooling in the downdraft.

The existence of middle latitude squall lines possessing extensive regions of trailing stratiform precipitation was recognized as long ago as Newton (1950), but this type of storm has not received much attention since then. An opportunity to observe such a system occurred on 22 May 1976 as an extensive squall line moved across Oklahoma. The line formed at ~1830 CST in association with a surface dryline near Oklahoma's western border. As the squall line moved eastward, it traversed the observational network of the National Severe Storms Laboratory (NSSL). A series of soundings bracketing the system's passage were carried out at nine NSSL stations. Conventional S-band radar data were obtained with NSSL's WSR-57 radar at Norman, Oklahoma, while Doppler measurements of the squall-line system were recorded by NSSL's S-band Doppler radars at Norman and Cimarron field (located approximately 40 km northwest of the Norman site) and the Illinois State Water Survey's CHILL radar stationed south of Anadarko, Oklahoma.

Ogura and Liou (1980) used the NSSL soundings to perform an extensive kinematic and thermodynamic study of the 22 May squall line. By employing a technique to composite sounding data, they found evidence of a mesoscale updraft-downdraft pair supported by mid-level convergence within the trailing region of the squall line, rather similar to the tropical squall system. The composite technique, however, revealed only the grosser aspects of the air motions and precipitation processes in the squall system (45 km was the minimum horizontal scale resolved). The radar observations obtained in this storm were not dealt with in detail by Ogura and Liou. In their conclusions, they stated that "A combination of detailed analysis of radar data with an analysis of rawinsonde data will undoubtedly provide a more complete description of the structure of squall lines." With this in mind, we have constructed vertical cross sections of reflectivity and radial velocity fields from NSSL's Cimarron Doppler radar (data from the other radars will be considered in the future) to examine further the similarity of the Oklahoma squall line to those observed in the tropics.

2. CONCEPTUAL MODEL OF THE OKLAHOMA SQUALL LINE

A conceptual model of the 22 May 1976 Oklahoma squall line (Fig. 2) has been synthesized from the study of the vertical cross sections. The two-dimensional airflow has been drawn to be consistent with the measured Doppler velocity components and the observed radar reflectivity structures in the cross sections.

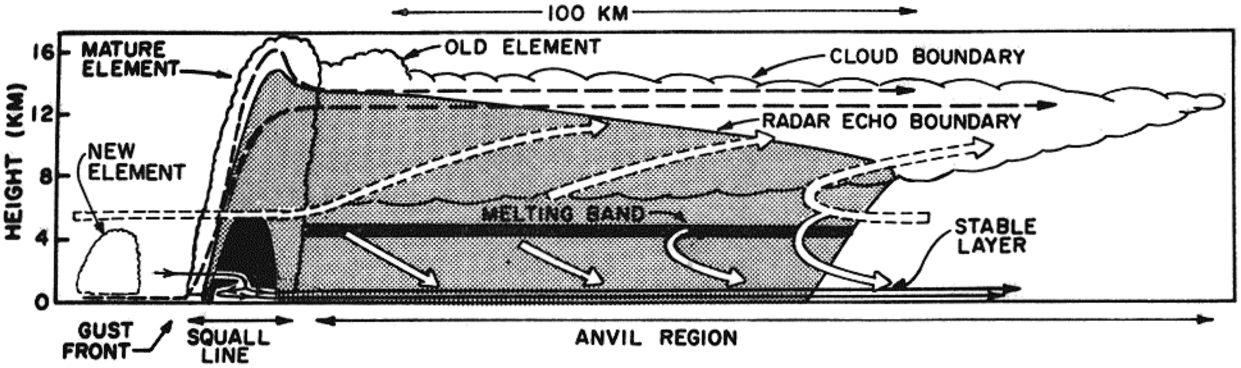

Figure 1. Schematic cross section through a typical tropical squall system. Dashed streamlines show airflow associated with convective-scale updrafts. Solid streamlines show convective-scale downdraft circulation. Associated with the trailing anvil, wide solid arrows show mesoscale updraft circulation. Dark shading shows strong radar echo in the melting band and in the heavy precipitation zone of the mature squall-line element. Light shading shows weaker radar echoes. Scalloped line indicates visible cloud boundary. From Gamache and Houze (1981).

The airflow into the front of the system is depicted as rising first above a "fine-line" echo associated with downdraft outflow and then progressing into the region of convective cells. A new cell, identified by a first-echo aloft, is shown at 60 km above the core of rising air, which was directed primarily into a weak-echo indentation on the leading side of a mature cell echo at 70 km. As the core of rising air approached the mature cell, it entered a stream of strong front-to-rear horizontal flow concentrated between 2 and 5 km. The updraft air therefore had a large horizontal component of motion and the core of the draft was tilted substantially. Upon reaching the tops of convective cells, the updraft air split into components directed to the front and rear of the system. The part directed forward carried ice particles into the leading anvil. As the particles fell into the inflow stream in mid-levels, they were either evaporated or swept back into the region of active cells.

Mature cells, such as the one at 70 km in Fig. 2., were followed by dissipating cells, such as the one at 90 km, which is shown as having lost its core of updraft air. The horizontal outflow of downdraft air was strongest under mature cells, but was also seen under the dissipating cells. Consequently, the forward-rushing downdraft air was seen at low levels throughout the region of forming, mature and dying cells (between 50 and 100 km in Fig. 2). Behind the region of cells (beyond 100 km in Fig. 2), the system-relative flow was everywhere directed from front to rear, except at the very back edge of the system where a bit of inflow was detected at middle levels.

The mid-level jet of front-to-rear flow extended through most of the region behind the cells, though it ended just before encountering the inflow from the rear at the back edge of the system. This jet was located just above the melting layer (indicated by the layer of high radar reflectivity between 100 and 170 km in Fig. 2). Houze (1981) showed that a

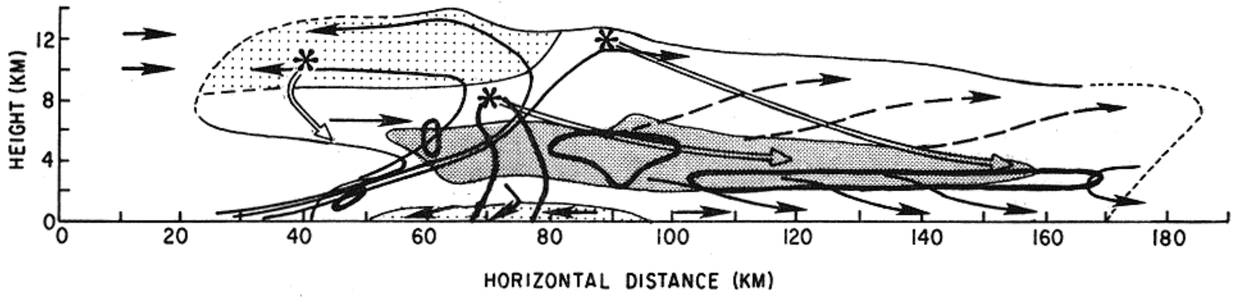

Figure 2. Conceptual model of the 22 May 1976 Oklahoma squall-line system. Outside contour outlines radar echo. Heavy lines denote regions of more intense echo. Light shading indicates regions of system-relative horizontal wind component directed from right to left. Heavy shading shows jet of maximum horizontal wind from left to right. System was propagating from right to left. Thin streamlines show two-dimensional relative flow consistent with observed wind and echo structure. Hypothesized ice particle trajectories are denoted by asterisks and double arrows. Environmental wind relative to the system is indicated just ahead of the leading anvil echo. Dashed lines indicate speculative parts of the model.

melting layer 100 km wide, to the rear of a convective line that is propagating by the successive development of new cells at its leading edge, can be explained by the relative horizontal motions of ice particles falling from the tops of cells. The particles move toward the rear of the system as a result of the continuing redefinition of the position of the leading edge of the system by the formation of new cells. In the Oklahoma squall line, this effect was present and exaggerated by the jet of particularly strong relative wind just above the melting layer. Hypothesized particle trajectories are indicated in Fig. 2.

Below the melting layer in Fig. 2, the air is shown to be subsiding. This feature is consistent with one-dimensional speed divergence observed below the melting layer borne out by vertical velocity calculations based on mass continuity and an assumption of no variations normal to the cross sections. Downdraft velocities averaged -50 cm/s at the 1 km level in the region below the melting layer. Attempts to calculate updraft velocites in the region above the melting layer were unsuccessful and the dashed streamlines in that region are somewhat speculative. However, the presence of mesoscale lifting in the lower troposphere in the region behind the convective cells is consistent with the results of Ogura and Liou (1980).

3. COMPARISON WITH TROPICAL SQUALL STRUCTURE

The conceptual models of the 22 May 1976 Oklahoma squall line (Fig. 2) and the tropical squall line (Fig. 1) have several notable similarities and differences:

(i) Both squall systems exhibit a gust front where the downdraft outflow from convective cells meets the inflowing air that feeds the convective updrafts.

(ii) A leading anvil produced by divergent outflow from cell tops was a feature of the Oklahoma squall line but is not usually associated with tropical squall lines, though exceptions have been noted by Hamilton and Archbold (1945) and Rappaport and Houze (1980).

(iii) Both the Oklahoma and tropical squall lines have been observed to progress by a combination of translation and discrete propagation. New cells systematically form on the leading edge. As they mature they become the main cells of the squall line. Dissipating cells occur to the rear of the mature cells.

(iv) The structures of the cells in the Oklahoma squall line differed markedly from the cells of tropical squall lines. The cells in the Oklahoma case appeared with a first-echo well aloft, exhibited weak echo regions in zones between the first echoes and mature cells and contained peak reflectivities centered aloft. The cells in tropical squall lines, on the other hand, exhibit their peak echo centroids at low levels, apparently as a result of their weaker updrafts (Caracena et al., 1979; Zipser and Lemone, 1980).

(v) A region of stratiform precipitation with a pronounced radar bright band at the melting layer is found in the trailing regions of both the Oklahoma and tropical squall systems. The stratiform region in the Oklahoma case, however, was only 70 km in width compared to the 100-200 km wide stratiform zones behind some tropical squall lines. In both the Oklahoma and tropical squall systems, the top of the radar echo in the trailing stratiform region exhibits a slope downward to the rear.

(vi) Relative flow is directed from front to back everywhere within the trailing stratiform portions of both the Oklahoma and tropical squall systems, except at their back edges, where inflow from the rear occurs in mid-levels. The front-to-back flow in the Oklahoma squall line was strongest in a middle level jet through the system, whereas in tropical systems the relative flow toward the rear is typically stronger at upper and lower levels and weaker in mid-levels (e.g., Gamache and Houze, 1981).

(vii) The melting layers in the stratiform precipitation regions of both the Oklahoma and tropical squall systems can be explained by the particles from the upper portions of cells drifting back relative to the system until they fall through the 0 deg C level. However, the mid-level horizontal wind maximum appears to play an additional role in spreading the particles across the trailing region in the Oklahoma case.

(viii) There is evidence of mesoscale updraft above the melting layer and a mesoscale downdraft below in both the Oklahoma and tropical squall lines.

This study has revealed details of the air motions and precipitation structure within an Oklahoma squall-line system that were not previously evident, even though the grosser aspects of the airflow had been derived from rawinsonde composites by Ogura and Liou (1980). This class of storm has striking similarities to, as well as some important differences from, tropical squall systems. Owing to its large region of associated stratiform rain, this type of storm is an important producer of precipitation. Further study of these systems should be directed not only toward verifying quantitatively the circulation pattern hypothesized in Fig. 2, but also determining the frequency with which such storms occur and their climatological contribution to precipitation.

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