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CONTENTS

ABSTRACT

The impact of satellite-derived cloud motion vectors on SESAME rawinsonde wind fields is studied in two separate cases (10 April 1979 and 9 May 1979). In addition, we assess the effect of wind and moisture gradients on the arbitrary assignment of the satellite data to coordinate surfaces in a severe storm environment marked by strong vertical wind shear. Low level cloud motion vectors are arbitrarily assigned to the 825 mb level and σ=P(vector)/P(surface)=0.9 level and also vertically interpolated to those levels. Objective analyses of SESAME rawinsonde winds and combined (SESAME winds and cloud motions) winds are produced and differences between these two analyzed fields are used to make an assessment of coordinate level choice. In addition, divergence and relative vorticity fields are derived from the SESAME winds and combined wind fields.

The results show that the standard method of arbitrarily <u>assigning</u> wind vectors to a "low level" coordinate surface yields systematic differences between the rawinsonde and combined wind analyses, which are primarily the result of the methods by which the cloud motion vectors are assigned to coordinate surfaces. Arbitrary assignment of cloud motions to the 0.9 sigma surface produces smaller differences than assignment to the 825 mb pressure surface. Additionally, systematic differences occur near moisture discontinuities and in regions of horizontal and vertical wind shears. The differences between the combined and SESAME wind fields are made smallest by vertically <u>interpolating</u> cloud motions to either a pressure or sigma surface. However, the accuracy of these interpolated

fields depends to a large extent on the methods used to determine cloud base levels and the vertical wind shear.

The inclusion of cloud motions vectors (CMV) enhances SESAME divergence and relative vorticity fields when the CMV are interpolated to either pressure or sigma coordinates. Interpolated CMV appear to add information to kinematic fields by better defining patterns consistent with physical mechanisms in the pre-severe storm environment. If forced to make arbitrary assignments, the use of the terrain-following sigma surface yields more consistent results than arbitrary assignment to a pressure surface in the lower troposphere.

1. Introduction

The practice of tracking clouds on geosynchronous satellite imagery to estimate environmental winds began with the acquisition of Applications Technology Satellite (ATS) data in the mid-sixties. The availability of improved (0.9 km) resolution satellite data from the SMS and GOES satellites in the mid-seventies greatly enhanced the capability for a better description of the large-scale wind fields over most of the globe and also made it possible to determine mesoscale wind features. Application of cloud motion vector (CMV) winds at synoptic scales was soon found useful especially over oceanic areas where conventional meteorological data were sparse. CMV have been employed in a number of tropical large-scale research projects (Hubert and Timchalk, 1972; Bengtsson and Morel, 1974; Suchman and Martin, 1976) and are now incorporated daily into the global analyses at the National Meteorological Center and at the European Centre for Medium Range Weather Forecasting.

The representativeness of cloud motions is difficult to assess at the mesoscale, and is most uncertain in an environment characterized by large vertical and horizontal wind shears and moisture gradients. These conditions are most often found in continental frontal situations in which severe thunderstorms typically form (Newton, 1963; Carlson and Ludlam, 1968). This is unfortunate since satellite cloud motion data would seem to offer great potential for study of the precursor storm environment, given the large number of cloud tracers which can be generated in these types of situations. Moreover, no comparisons have ever been made between CMV and mesoscale rawinsonde observations obtained in baroclinic, continental situations. Despite this lack of adequate verification, a number of investigators have obtained physically meaningful mesoscale wind fields from satellite cloud motions in continental severe storm situations (Wilson and Houghton, 1979; Peslen, 1980; Negri and Vonder Haar, 1980). Furthermore, the mesoscale information of CMV has been reported by Maddox and Vonder Haar (1979) in terms of statistical structure functions.

The validity and practical application of CMV fields depend upon answers to the following interrelated questions:

(1) Cloud motion representativeness: At what level or in what layer is the cloud motion most representative of the environmental winds?

(2) Cloud height determination: How do current methods of measuring cloud height impact the assignment of cloud motions to a representative level in the atmosphere?

(3) Coordinate surface selection: Given that objective analyses, diagnostic computations and numerical models require data at a discrete number of vertical levels, can the variation in cloud heights between CMV (whether at cloud base or cloud top) be accommodated by arbitrarily assigning the group of CMV to a single coordinate surface?

The cloud motion representativeness and cloud height determination issues have been addressed in numerous studies as summarized in Section 2. The representativeness issue, which remains a subject of considerable controversy, is concerned with the difficulty of separating cloud motion from the complicating effects of cloud evolution during the tracking interval. The height determination issue is concerned with errors arising from the various methods of cloud height measurement. Together these two sources of error can contribute to a very large percentage of the total random error variance [for example, 93% in the case reported by Wilson and Houghton (1979), amounting to 4.5 m sec^{-1} standard deviation in the resulting CMV wind estimates].

It has been the customary practice in coordinate surface selection to arbitrarily assign CMV to a single pressure level categorized as either "low," "medium," or "high" based on a bi-spectral satellite method that estimates cloud top height (Suomi, 1975). The sensitivity of CMV wind analyses at these arbitrarily assigned levels to the use of cloud base level, cloud top level, a "level of best fit" (Hubert and Whitney, 1971), and a cloud layer method for cloud vector assignment is discussed by Lee (1979). However, even with more accurate stereographic methods of determining cloud heights (Hasler, 1981) or VAS radiances (Menzel et al., 1983) and a perfect understanding of cloud motion/environmental wind relationships, the variation of cloud heights across the tracking area introduces another source of error when arbitrarily assigning these vectors to a single "low," "medium" or "high level." These errors can also create problems in applying CMV to diagnostic or modeling studies. This problem of coordinate surface selection may be worse in areas in which there is a variation of cloud base levels across regions of strong horizontal moisture gradients and in an environment characterized by significant vertical wind shear.

The purpose of this paper is to assess the impact of coordinate surface selection upon both the wind analyses and the computations of kinematic fields derived from low-level CMV data in pre-convective environments characterized by strong vertical wind shear. Two SESAME cases are chosen to determine the effect of wind and moisture gradients on the assignment of CMV to two kinds of coordinate surfaces. These two cases

(9 May 1979 and 10 April 1979) exhibit radically different conditions of horizontal moisture homogeneity and vertical wind shear. This represents the first time that a comparison has ever been made between CMV and mesoscale rawinsonde observations obtained from a special network in highly baroclinic, continental situations. In Section 2 we review the methods used to assign heights to individual cloud motion vectors and the associated cloud representativeness and height determination problems. Section 3 describes the SESAME and satellite data and the methodology used in the two case studies. Sections 4 and 5 contain analyses of meteorological conditions during the cloud tracking period and an examination of the causes of systematic variations in the map analyses of velocity and divergence between the rawinsonde wind data and the combined (rawinsonde and cloud motion) wind data for 9 May and 10 April, respectively. The results are summarized in Section 6.

2. Factors contributing to the uncertainty in CMV level assignment

a. Unrepresentativeness of cumulus cloud motions

The degree to which cumulus cloud movement represents ambient air motion depends upon the environmental wind shear, the cloud-base wind, and the cloud properties (vertical ascent rate, entrainment of clear air, and form drag). In the absence of vertical wind shear, small cumuli usually move with the air velocity at cloud base levels (Malkus, 1949). However, since cloud slope changes in response to any change in the intensity of the cloud updraft, the apparent movement of the cloud with respect to the wind (Malkus, 1952) will be impacted. The location, rate of generation, and vertical ascent rates of new cloud turrets can also complicate the relationships between cloud and wind velocities. Typically, new growth occurs on the upshear side of medium-sized cumulus (Higuchi, 1965; Warner et al., 1980). A number of studies have revealed that in a wind field turning with height, the cloud base moves with the wind at that level whereas the top portion of the cloud may move in a very different direction (Higuchi, 1965; Purdom et al., 1984). The life stage of the cloud must also be considered, as it has proven difficult to obtain meaningful cloud velocities by tracking dissipating clouds. (Such a cloud often will either split into two clouds or have its top separated from the convection center because of the destructive effects of vertical wind shear.)

When cumulus motions are determined from satellite imagery, the relationship of cloud nature to the image frequency and resolution must also be considered (Hubert, 1979). The most representative cumulus have diameters of 1-3 km. Typical tracking periods of 10-20 min using 3 min interval (rapid scan), high resolution (0.9 km) GOES data allow for continuous recognition of rapidly-changing cumulus tracers. These kind of data greatly increase the number of tracers over that available using lower resolution, lower frequency imagery. Use of the 3 min interval data over a 15 min tracking period gives more accurate results because of the overdetermination of cumulus velocities. Yet in spite of this advantage, the longer tracking period allows for the cloud to evolve (grow or decay) and may also result in inadvertent tracking of the cloud top, side, and base at different times during the tracking period (Purdom _et al._, 1984).

This discussion has highlighted the various problems involved in distinguishing cloud evolution effects from that cumulus motion which is representative of the environmental winds at some level or in some layer. However, despite these problems, experimental results appear to support a general relationship between cloud motions and air motion. In the weakly-sheared tropical enviornment, rawinsonde-measured winds have been shown to agree well with low level CMV measured from satellites (Hubert and Whitney, 1971; Fujita _et al._, 1975; Bauer, 1976; Suchman and Martin, 1976). Excellent comparisons have also been made between aircraft-determined motions of oceanic trade cumulus and _in situ_ wind measurements (Hasler _et al._, 1979). The latter study showed that the average magnitude of vector differences between cloud motions and the winds was minimized at cloud base level. The same study also found that oceanic cumuli in frontal regions agreed best with the mean winds in the cloud layer. The only attempt ever reported at intercomparing aircraft wind measurements and aircraft-estimated cloud motions _over land_ was a study of three cumulus clouds by Wagner and Telford (1976), which showed best agreement (± 1.5 m sec^{-1}) with the winds just below cloud base. Thus, it remains uncertain whether cumulus clouds in baroclinic (frontal) situations over land are most representative of the winds at cloud base or at some other level.

b. Errors in measurement of cloud heights

Cloud top heights can be estimated by a bi-spectral satellite method that compares the cloud top infrared temperature with a standard atmospheric temperature-pressure sounding, corrected for latitude and date. A variation of this technique (Suomi, 1975) used by Wilson and Houghton (1979) and Peslen (1980) calculates optical thickness from the visible brightness of a target cloud to determine the infrared emittance of the cloud and thus account for fractional cloud cover on a sub-pixel scale. Preliminary estimates of the absolute accuracy of this algorithm by Smith (1975) are ±50 mb for low clouds, but can be as much as ±100 mb when compared to "ground truth" measurements made by rawinsonde and aircraft (Lee, 1979). This cloud top method is typically used in conjunction with other information (surface reports of cloud bases, sounding data, and the "level of best fit"--discussed below) to assign the low-level CMV to a pressure level somewhere between 950 mb and 700 mb. A more reliable method for measuring cloud top heights utilizes stereographic observations of clouds from two geosynchronous satellites simultaneously scanning a mutual overlap region (Hasler, 1981). Although this method is capable of determining cloud top heights to ±0.5 km (±50 mb), it is limited to the overlap area and is possible only when the measurements from the satellites are synchronized to within a couple of minutes. A third method developed by Menzel et al. (1983) claims similar accuracy by using recently available infrared multiple channel data from the Visible Infrared Spin-Scan Radiometer Atmospheric Sounder (VAS) to assign simultaneous heights and velocities of cloud motion winds. However, this accuracy is unobtainable when the differences of radiometric measurements from the various channels fall to low values, a situation which can occur for low clouds. Summarizing the various methods for obtaining cloud top heights, it may be said that the uncertainty in estimating low-level clouds is in the range of 50-100 mb, which is large enough to adversely affect calculations of kinematic parameters when vertical wind shear is strong.

c. Uncertainty in level assignment of CMV

The uncertainty in CMV level assignment is mainly the result of limitations i current methods of measuring cloud heights and an insufficient understanding of cloud motion/environmental wind relationships. However, even if these errors did not exist, the variation of the optimum assignment level from cloud to cloud across the tracking area will introduce horizontal velocity gradients. This variability arises from the effects of vertical wind shear as the CMV values are vertically interpolated from their respective assignment levels to a particular coordinate surface. This interpolation procedure is a pragmatic requirement for either numerical model assimilation or for making diagnostic calculations from objective analyses of the CMV data. In the presence of uniform vertical wind shear, the greater the vertical separation between assignment level (e.g., cloud base) and these selected coordinate surfaces, the greater the difficulty in applying CMV data to modeling and diagnostic studies.

The cloud top height assignment methods are all subject to the criticism that experimental evidence (at least in non-frontal situations over the tropics) shows best agreement between cloud motion vectors and rawinsonde winds at cloud base levels (e.g., Hubert and Timchalk, 1972; Hasler et al., 1979). Though cloud base levels cannot be measured reliably from geosynchronous satellites, they may be estimated from surface station reports. Lee (1979) found that use of oceanic cloud base heights produced an objective analysis of winds in better agreement with satellite imagery than any other assignment level. It remains uncertain whether inter-station variation in cumulus cloud bases over land can significantly affect mesoscale CMV wind analyses.

The cloud layer method assigns CMV values to all levels in-between the cloud top and cloud base levels for a given cloud. This method attempts to account for the fact that the motion of a cloud is affected by entrainment and shear (Malkus, 1952), and hence is an integrated effect of cloud growth rate and the vertical variation in the horizontal winds. Actually, this method lacks true physical realism, and limited experiments indicate that it simply results in an average of the cloud top and cloud base methods (Lee, 1979).

Another method sometimes used to assign CMV data to a level is the "level of best fit" (LBF) method developed by Hubert and Whitney (1971). The LBF is the level at which the vectorial difference between cloud velocity and rawinsonde-derived wind velocity is the smallest. This assignment method may produce unreasonable results where the vertical wind shear is small, since the CMV may agree well with the winds throughout a deep layer. However, use of the LBF in conjunction with surface reports of cloud bases and sounding data has produced reasonable and informative mesoscale wind analyses in highly sheared frontal situations (Peslen, 1980; Negri and Vonder Haar, 1980).

This review highlights the various approaches to assigning the CMV to a particular level. It may be argued, however, that all of the finer aspects of each technique may have no meaningful impact on diagnostic computations if the next step in the analysis procedure is to "arbitrarily" assign all the CMV to pressure surfaces which are representative of "low," "middle," or "high" portions of the troposphere as has been done in numerous diagnostic or model studies (Wilson and Houghton, 1979; Peslen, 1980; Negri and Vonder Haar, 1980; Lee and Houghton, 1984a, b). The purpose of the analyses which follow is to determine the impact of the arbitrary assignment of CMV to a "low" pressure surface in a pre-convective storm environment.

3. Data and analysis procedures

a. Data

High resolution (3 hourly, 25 mb vertical interval, 200 km horizontal spacing) sounding data acquired from the AVE-SESAME regional scale network (Alberty et al., 1979) for 2000 GMT 9 May 1979 and for 1800 GMT 10 April 1979 are used to create SESAME rawinsonde wind and moisture data sets for the 825 mb and σ=0.9 levels. These high resolution regional scale data are critical in our analyses since spatially dense and timely soundings are necessary to relate afternoon atmospheric conditions such as vertical wind shear and moisture discontinuities to vector differences between combined (SESAME and CMV) wind data and SESAME wind data. Additional information on the SESAME data and on the SESAME-scale network can be acquired from Alberty et al. (1979). The sigma (σ) coordinate system, where σ is the pressure of the CMV divided by the surface pressure, is chosen for comparison to the pressure (p) system (typically used in CMV studies) because (1) the effect of topography (or cloud base variations) is accounted for by the inclusion of surface pressure in the definition of σ, and (2) CMV can be easily inserted into mesoscale models which frequently employ σ coordinates (e.g., Anthes, 1978; Kaplan et al., 1982).

Cloud heights and motions are acquired through the use of the interactive computer display system known as the Atmospheric and Oceanographic Information Processing System (AOIPS), described by Billingsley (1976). This system uses the bi-spectral cloud top height algorithm (Suomi, 1975) to differentiate clouds into three layers. Only low level clouds are studied in this research effort. Clouds were assumed to approximate the environmental winds at their cloud base levels. Surface reports and SESAME soundings were used to obtain an estimate of the cloud base heights, which were found to generally correspond to the "level of best fit" in both the 10 April and 9 May case studies. The 825 mb and σ=0.9 levels are chosen as "typical" assignment levels because they are generally considered to be average "low" levels. These levels are only one pair of many possible "low" levels which could have been considered appropriate. The selection of, for instance, the 850 mb and σ=0.89 levels would also have been adequate to satisfy our objectives. In any case, the results are similar regardless of the choice of "typical" assignment levels.

The procedures for interactive cloud tracking, navigation, and error estimation are given by Peslen (1980). Briefly, CMV are acquired by cloud tracking from a time-lapsed loop of four 3 min interval visible GOES pictures. High resolution (3 min, 0.9 km) satellite image data are used to assure continuity in following selected cloud motions in the image sequence. Small cumulus clouds (0.5-3.0 km in diameter) are chosen as tracers to infer environmental winds at cloud base levels. Their brightness or geometric centers are chosen as the tracking point to decrease the influence of the clouds' own development or dissipation on the calculation of its motions. Low level cumulus tracers were considered acceptable if (1) they had cloud tops $\leq$2.5 km and (2) the magnitude of the vector difference between any two consecutive vectors in the GOES image sequence was $\leq$5 m s^{-1}. This latter criterion is used to avoid selecting clouds with erratic motions not representative of the environmental winds.

Figs. 1 and 2 display the regional scale SESAME rawinsonde wind data at 825 mb and σ=0.9 and low level cloud motion vectors for 9 May and 10 April, respectively. Rawinsonde stations are regularly spaced at approximately Δn=200 km. More closely spaced rawinsonde data were available at the "storm scale" on 9 May, but were not utilized because of the difficulty in doing a meaningful objective analysis upon such densely spaced data clustered within the less dense regional scale network. The CMV are irregularly spaced due to the presence of wave clouds and middle level clouds on 9 May, and to the absence of clouds or the presence of middle to high level clouds on 10 April.

b. Difference map technique

The velocity differences between rawinsonde winds and CMV at the two

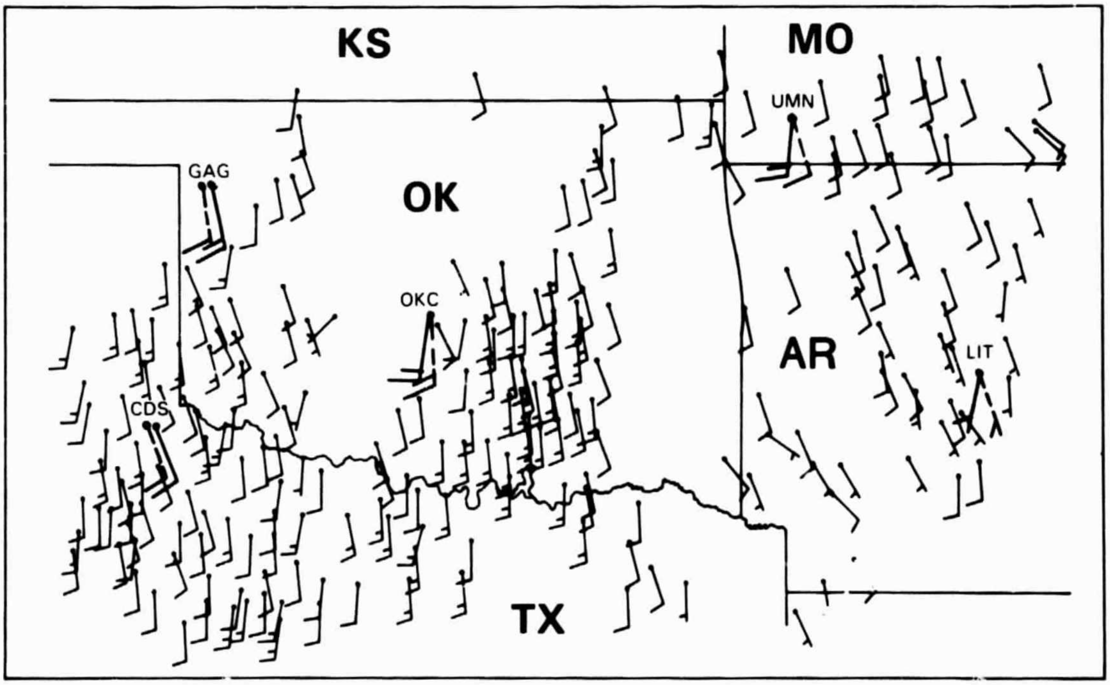


Figure 1. Regional scale SESAME rawinsonde winds and low level cloud motion vectors for 2000 GMT 9 May 1979. Bold-face rawinsonde station winds are located at 825 mb (solid barb) and σ=0.9 (dashed barb). Wind barbs have units of m s^{-1} (one flag = 10 m s^{-1}).

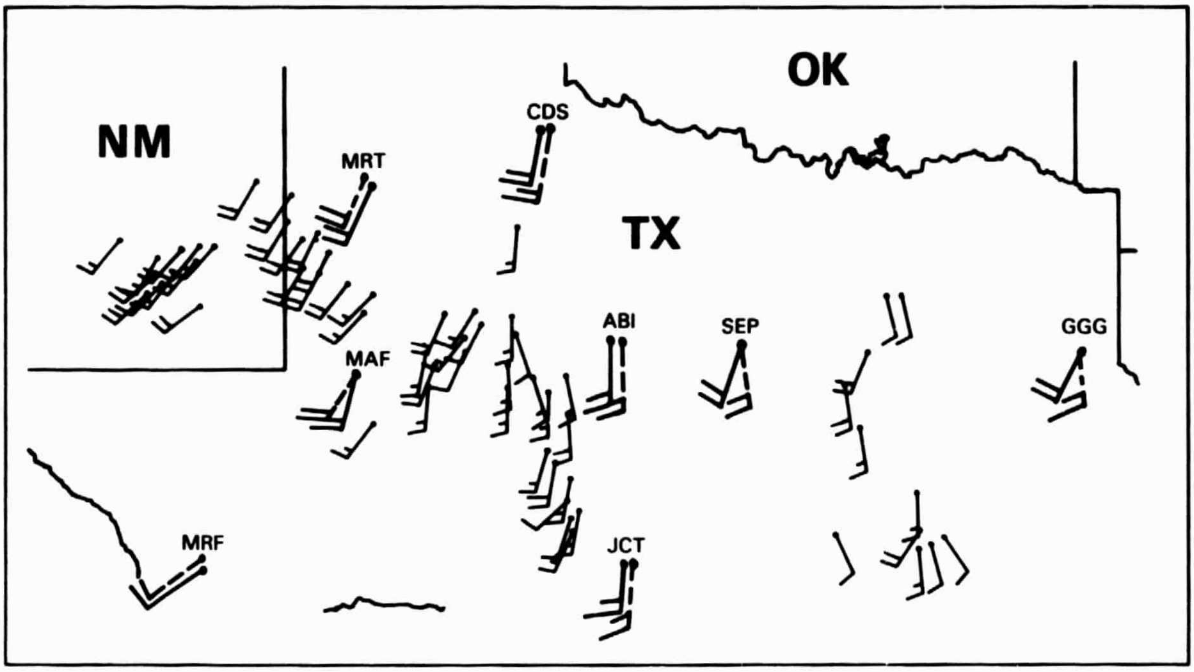


Figure 2. Same as Fig. 1 except for 1800 GMT 10 April 1979.

coordinate levels are determined from objective analyses of the data. The impact of arbitrarily assigning the CMV to 825 mb and σ=0.9 is first assessed by computing vector differences between grid point values of the combined (radiosonde and CMV) winds and the radiosonde winds only, as suggested by Browning (1980). The grid point values are determined from a Barnes (1973) interpolation scheme modified for our specific needs (Koch et al., 1983) as described in the Appendix. Grid point values of the SESAME data are subtracted from those values of the combined data, resulting in vector difference maps which show the impact of the cloud motions on the conventional wind fields. Because of measurement error (Fuelberg, 1974) only vector differences in the wind larger than 3 m s^{-1} are considered significant in comparing rawinsonde winds and CMV.

The entire approach is then repeated for CMV linearly interpolated to 825 mb and σ=0.9. Least squares fits to the vertical profile of winds at the rawinsonde stations are calculated to obtain useful profiles for estimating vertical wind shears. Vertically-averaged wind shears are computed between selected "standardized" shear layers of 875-775 mb and σ=.950-.875. These layers are selected because they most often represented the average wind shear environment surrounding the arbitrarily selected levels of 825 mb and σ=0.9. The vertical wind shears calculated at the rawinsonde stations are then horizontally interpolated to satellite data locations. The analysis techniques are discussed in the Appendix.

4. 9 May 1979 case study

a. Synoptic and storm scale analyses

Thunderstorms with accompaning severe weather developed after 2100 GMT on 9 May 1979 in the Texas and Oklahoma Panhandles within the convectively unstable atmosphere ahead of a stationary front. Ogura et al. (1982) and Carlson et al. (1983) have made detailed analyses of this case. The 2000 GMT surface hourly analysis (Fig. 3) shows a subsynoptic low pressure system in the Texas Panhandle, a stationary front separating cool, dry northerly air from warm, moist tropical air, and a dryline marking the leading edge of continental tropical air in southwest Texas. The area of CMV data centered in Oklahoma (Fig. 1) is located within a relatively homogeneous air mass in that the surface-850 mb dew points are fairly uniform in this area.

An accompanying isentropic cross section (Fig. 4) between Amarillo (AMA), TX and Little Rock (LIT), AR (refer to A-A', Fig. 3 for locations) shows a well mixed layer above an undulating restraining inversion, or "lid" (somewhere in the 750-825 mb layer) east of Gage (GAG), OK. The western edge of the lid is located near the stationary front and west of Hinton (HNT), OK at 2000 GMT. This location is of primary interest since severe thunderstorms first developed at 2100 GMT between this lid edge and the cold front near the Texas-Oklahoma border. Carlson et al. (1983) discuss further the importance of the lid on 9 May 1979. There are only moderate vertical wind shears across Oklahoma despite the presence of the strong inversion. The most significant aspects of the wind field for this study are (1) the horizontal variation of the vertical wind shear in the plane of the cross section, (2) the relatively strong vertical wind shears at AMA and GAG, and (3) the considerable directional shear at LIT.

b. Results of the evaluation of the CMV data set

Fig. 5 shows the magnitude of the vector differences in wind between the combined winds and SESAME winds for (a) CMV arbitrarily assigned to 825 mb, (b) CMV interpolated to 825 mb, (c) CMV arbitrarily assigned to

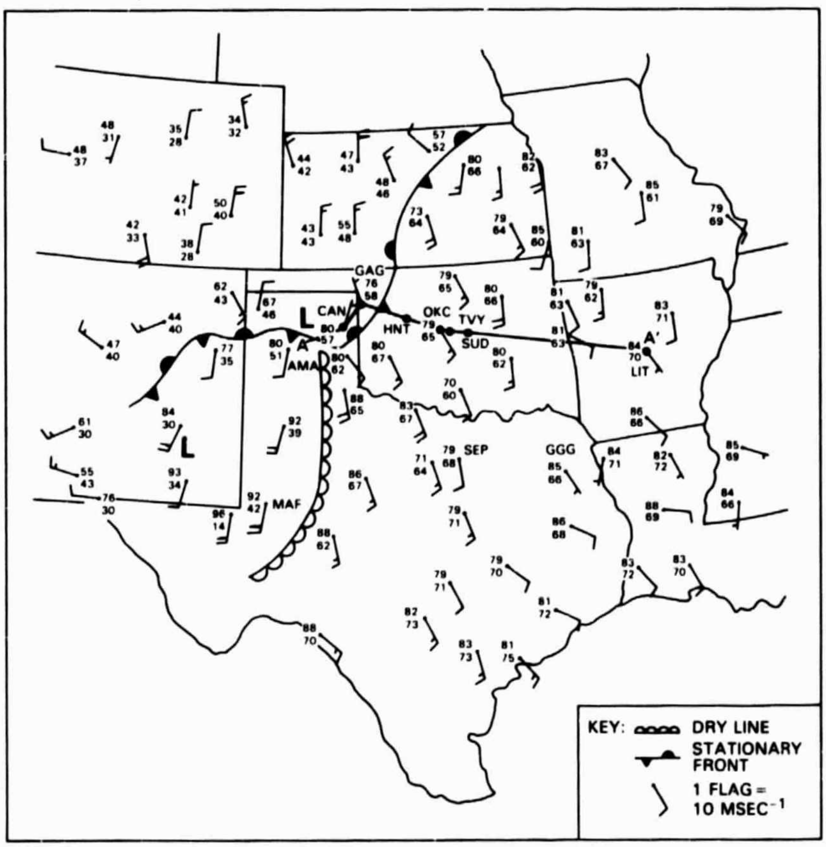


Figure 3. The 2000 GMT surface hourly analysis for 9 May 1979. Temperatures and dew points in (^{o}F) are plotted next to each surface station. Wind barbs have units of m s^{-1} (one flag= 10 m s^{-1}). Line A-A$'$ refers to a cross section analysis in Fig. 4.

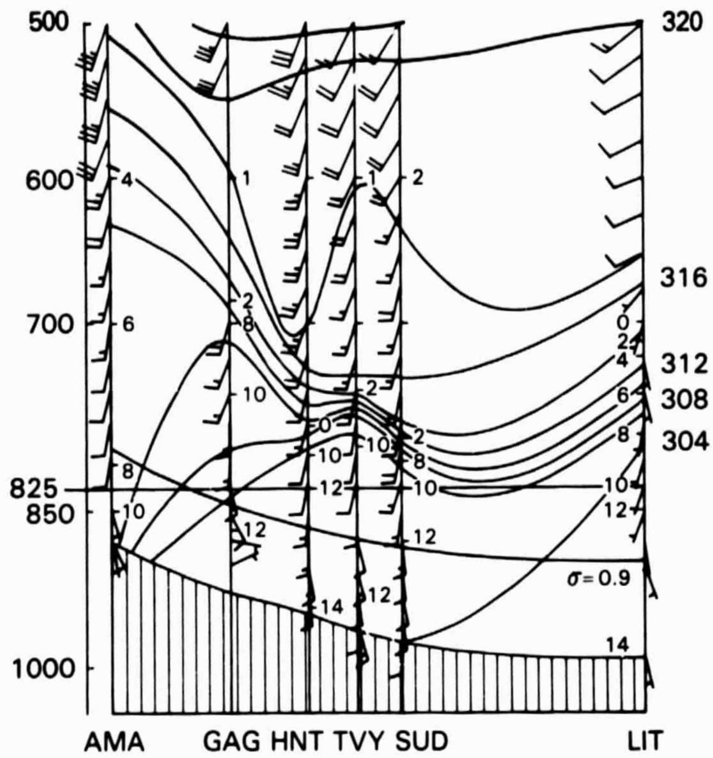


Figure 4. Vertical cross section from Amarillo (AMA), TX to Little Rock (LIT), AR along a sequence of stations A-A′ in Fig. 3 for 2000 GMT 9 May 1979. Solid lines correspond to isentropes (°K), single and double digit numbers refer to mixing ratios (g kg^{-1}), and one flag (✓)=10 m s^{-1}.

σ=0.9, and (d) CMV interpolated to σ=0.9. Arbitrary assignment of CMV to 825 mb (Fig. 5a) produces vector differences in the wind $\geq$3 m s^{-1} throughout the eastern half of the domain. A comparison of the CMV speeds and directions in Fig. 1 with the vertical profile of rawinsonde-observed winds (Fig. 4) reveals that the large vector differences in the eastern half of the analysis domain in Fig. 5a are primarily due to improperly assigning the CMV too high in the atmosphere (at 825 mb) in the presence of vertical wind shear. Fig. 6 shows the location of cloud tracers relative to coordinate surfaces and reveals the impact of vertical wind shear on the arbitrary assignment of CMV. Lower level (~875-900 mb) clouds, which are embedded in a southeasterly flow near the surface in eastern Oklahoma and Arkansas, are being assigned to a level of stronger southwest winds at 825 mb (see Fig. 4). The result of this assignment is to decrease the overall wind speed and give the wind a spurious southeasterly component at 825 mb. Choosing a higher pressure level (e.g., 875 mb) to eliminate this problem in eastern Texas introduces other problems in the western part of the analysis domain because it would result in assigning CMV much too low over the Texas Panhandle (Fig. 6). The problem is that the customary assignment of cloud motions to an isobaric surface is not physically realistic, because cumulus clouds in this case do not lie near a unique pressure level but rather tend to follow the terrain as it slopes upward toward the west.

The interpolation of CMV to 825 mb (Fig. 5b) results in smaller vector differences everywhere except in the Texas Panhandle. The smaller vector differences are the result of the ability of the interpolation routine to account for the clouds' level and the vertical wind shear which surrounds the cloud. The larger vector differences west of Canadian (CAN), TX are partially due to the fact that cloud bases, which were determined from rawinsonde-scale surface reports and sounding data and then horizontally interpolated to satellite data points, were not reported anywhere behind the surface cold front or dryline. Notice that the 3 $m\ s^{-1}$ vector difference isotach parallels the dryline-frontal system in the Texas Panhandle (Fig. 3). This resulted in poor specification of actual cloud bases in the eastern Texas Panhandle where clouds were tracked. It appears that these clouds had bases higher than 825 mb. That is, the CMV speeds

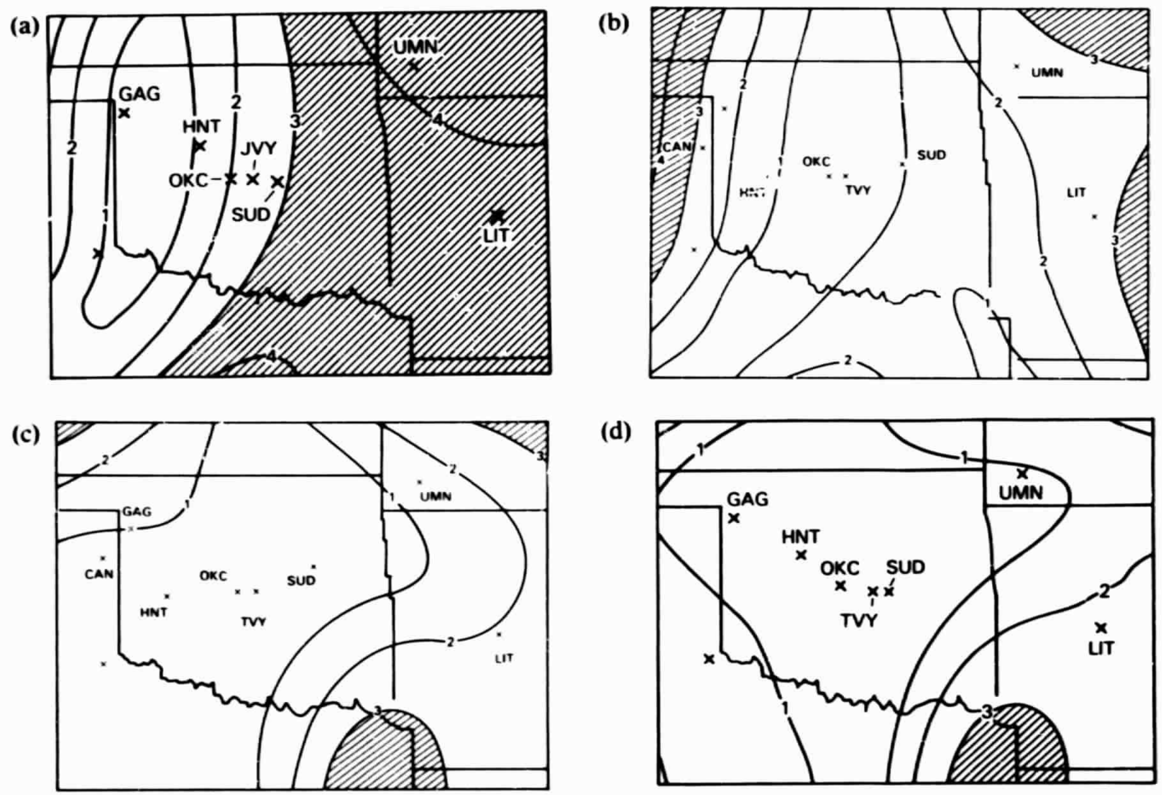


Figure 5. Magnitude of the vector differences in wind ($m\ s^{-1}$) between combined (SESAME and CMV) winds and SESAME winds at 2000 GMT 9 May 1979 for CMV (a) arbitrarily assigned to 825 mb, (b) interpolated to 825 mb, (c) arbitrarily assigned to σ=0.9, and (d) interpolated to σ=0.9. Vector differences $\geq 3\ m\ s^{-1}$ are shaded.

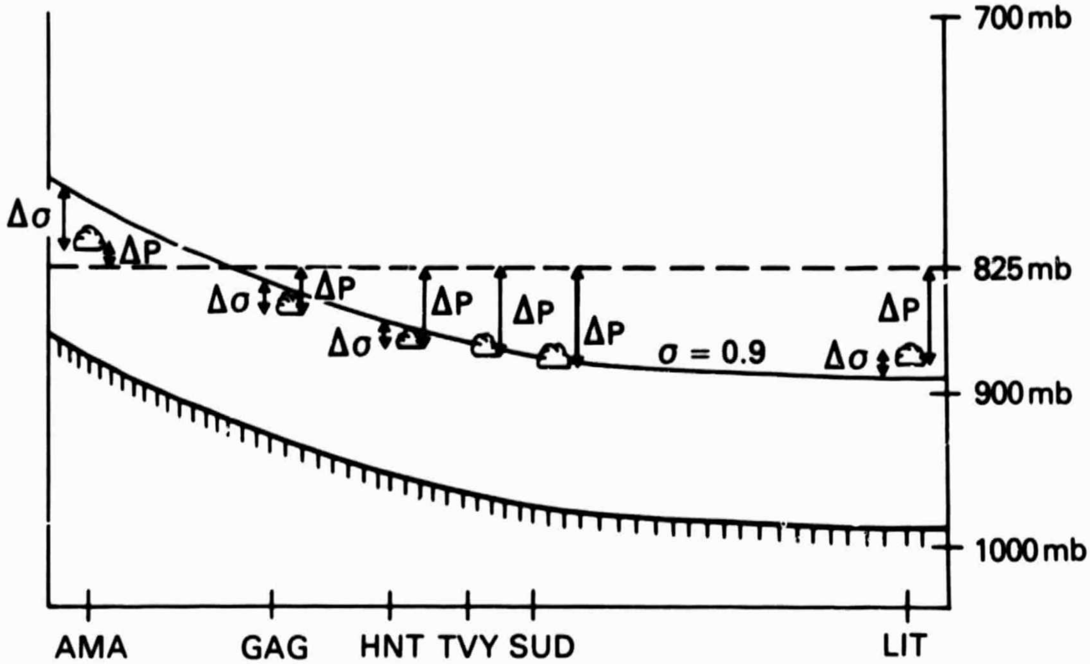


Figure 6. Schematic diagram showing the location of cloud tracers (☁) relative to the p=825 mb and σ=0.9 coordinate surfaces at selected stormscale rawinsonde stations for 2000 GMT 9 May 1979.

are higher and the directions are more southwesterly than the winds obtained from the rawinsondes. It is also possible that use of cloud bases for the purpose of vertical interpolation may be inappropriate in the frontal zone, since there is some evidence to suggest that cumulus clouds move more with the winds at their mid-levels in frontal situations (Hasler et al., 1979).

Arbitrary assignment of CMV to σ=0.9 (Fig. 5c) shows comparatively smaller vector differences than for the 825 mb assignments because the arbitrary assignment of CMV to σ is done through a smaller depth (Δσ) of the atmosphere (Fig. 6). Cloud base levels in this case followed closely the slope of the terrain and consequently the slope of the low level σ surface. Southeasterly CMV (at cloud base levels between σ=.93 and σ=.88) are very similar to the southeasterly SESAME winds at σ=0.9. For the 825 mb case, these same southeasterly CMV are being assigned to a level of strong southwest winds within a deeper layer of vertical wind shear.

A comparison between arbitrary assignment and interpolation of CMV to σ=0.9 (Figs. 5c and 5d) shows little variation between the results. The small variation results from interpolation done through a small $\Delta\sigma$=.03 between cloud bases and the σ=0.9 surface. The product of this small $\Delta\sigma$ and the estimated vertical wind shear term changes only slightly the original u and v components of the CMV. Recall that a different relationship exists between arbitrary assignment and interpolation of CMV to 825 mb (Figs. 5a and 5b). Interpolation is done through a larger layer (ΔP=65 mb) between cloud bases and 825 mb which results in larger differences between arbitrary assignment and interpolation to a pressure level (Figs. 5a and 5b).

Fig. 7 shows 825 mb divergence fields derived from (a) SESAME winds, (b) SESAME winds and arbitrarily assigned (noninterpolated) CMV, and (c) SESAME winds and interpolated CMV. The 825 mb SESAME winds are generally divergent across Oklahoma and Arkansas (Fig. 7a) as a consequence of the combination of southeasterly flow at CDS, AMA, and GAG and south-southwesterly flow at OKC, LIT, and UMN (see Fig. 1). The arbitrary assignment of CMV to 825 mb (Fig. 7b) produces a convergent wind field across Oklahoma resulting from the addition of CMV which display directions from the south-southwest in the Texas Panhandle and from the southeast in eastern Oklahoma (see Fig. 1). The overall effect of assigning CMV to 825 mb SESAME winds is to weaken divergence across the entire cloud tracking area. The interpolation of CMV to 825 mb (Fig. 7c) also weakens the overall divergence field, but the resultant field is very different from both the SESAME field and the combined field with arbitrary assignment of CMV. The wind field is divergent in western Oklahoma and convergent in eastern Oklahoma and Arkansas. The interpolated CMV (not shown) are more southerly in western Oklahoma, more southwesterly in eastern Oklahoma, and less southeasterly in Arkansas than their noninterpolated counterparts in Fig. 7b.

Fig. 8 shows divergence fields derived from the various analyses at the σ=0.9 level. A comparison between the SESAME divergence fields at 825 mb (Fig. 7a) and at σ=0.9 (Fig. 8a) shows major differences between the two fields. Whereas the 825 mb winds are mostly divergent across Oklahoma and Arkansas, the σ=0.9 winds are convergent in western Oklahoma and divergent in eastern Oklahoma and Arkansas. The convergent wind field in western Oklahoma at σ=0.9 is a consequence of the surface being located within the moist southeasterly air east of the frontal zone (see Fig. 4). Since the southeasterly flow does not extend to 825 mb, the SESAME divergence fields on that pressure surface over central Oklahoma are different than the fields on the σ=0.9 surface. The arbitrary assignment of CMV to σ=0.9 (Fig. 8b) weakens both the divergence in eastern Oklahoma and Arkansas and the convergence in western Oklahoma. CMV are slightly stronger and more south-southwesterly in western Oklahoma and Arkansas and more southeasterly in eastern Oklahoma than the SESAME winds. The divergence field derived from CMV interpolation (Fig. 8c) is very similar to the field derived from CMV arbitrary assignment (Fig. 8b). Recall, on the other hand, that there were significant differences between the divergence fields produced by arbitrary assignment and vertical interpolation to the 825 mb level (Fig. 7). Given these differences and

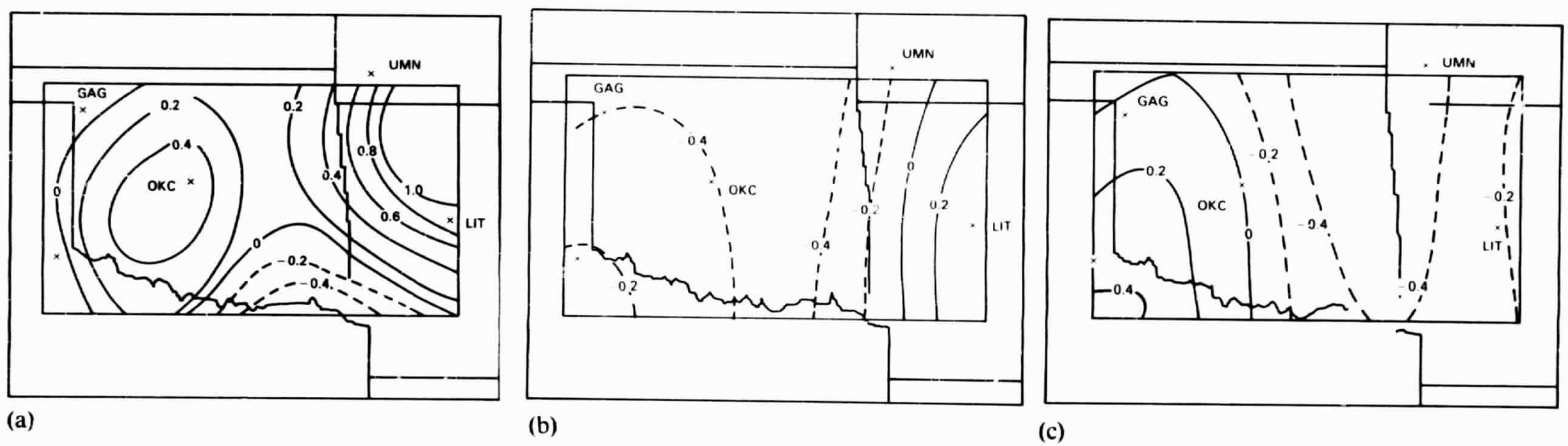


Figure 7. 825 mb divergence fields (units =x 10^{-5} s^{-1}) for 2000 GMT 9 May 1979 derived from (a) SESAME winds only, (b) combined SESAME winds and arbitrarily assigned (noninterpolated) CMV, and (c) combined SESAME winds and interpolated CMV. Solid lines are contours of divergence; dashed lines are contours of convergence.

the results in Fig. 5, these analyses suggest that if accurate shear vectors at the mesoscale are not available for interpolating CMV to a level, and we are instead forced to rely upon an arbitrary assignment of the CMV to a "low" level, then the σ coordinate system has decided advantages over the pressure coordinate system for calculating the cloud motion-based divergence fields for the lower troposphere.

Relative vorticity fields have been similarly acquired for 9 May. Differences among the vorticity fields computed using the various level assignments to σ and p surfaces were small (not shown).

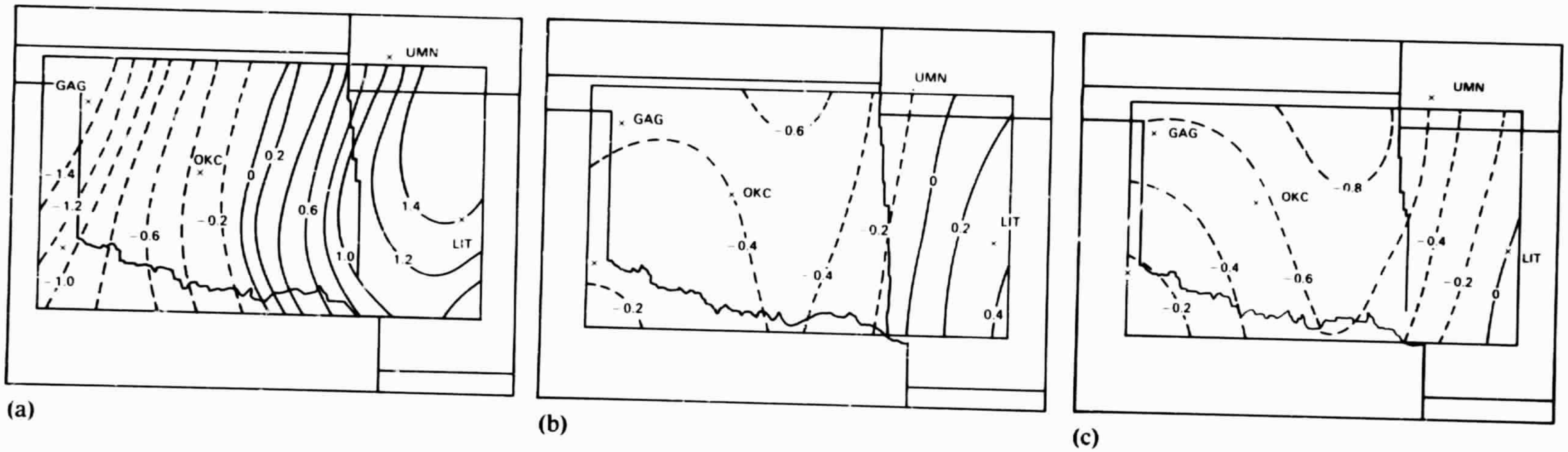


Figure 8. σ=0.9 divergence fields (units= x 10^{-5} s^{-1}) for 2000 GMT 9 May 1979 derived from (a) SESAME winds only, (b) combined SESAME winds and arbitrarily assigned (noninterpolated) CMV, and (c) combined SESAME winds and interpolated CMV. Solid lines are contours of divergence; dashed lines are contours of convergence.

5. 10 April 1979 case study

a. Synoptic and regional scale analyses

Severe thunderstorms with associated tornadoes, funnel clouds, hail, high winds and heavy rains developed in the northern Texas Panhandle and, later, in north central Texas and southern Oklahoma between 1800 GMT and 0200 GMT on 10 April 1979. The 1800 GMT surface hourly analysis (Fig. 9) shows a cold front extending from an intense low pressure system in Colorado to the Texas-Mexico border. The initial thunderstorm activity began at 1800 GMT south of AMA and due north of a dryline bulge in western Texas (Alberty et al., 1979). The initial outbreak of severe thunderstorms moved eastward by 2100 GMT toward the warm front in north central Texas where more intense storms developed in the Red River Valley. See Carlson et al. (1983), Moore and Fuelberg (1981), and Kocin et al. (1982) for details concerning this case.

Analyses of the 1800 GMT SESAME regional scale soundings (Figs. 10 and 11) show southwesterly flow at all levels within a deep well-mixed layer at stations at and west of the dryline, except for ABQ, which was behind the cold front. To the east of the dryline, moist air characterized by southeasterly winds lies underneath the drier mid-level air characterized by southwesterly winds. This case is similar to 9 May 1979 in that warmer, drier air at mid-levels originating from Mexico has been differentially advected over the cooler, moister air from the Gulf of Mexico, thus contributing to the development of a restraining inversion, or "lid" over southern and eastern Texas and Louisiana (Carlson et al., 1983). However, this case is different from the other case in that: (1) CMV are fewer and farther between (Fig. 2); (2) vertical wind shears are stronger throughout

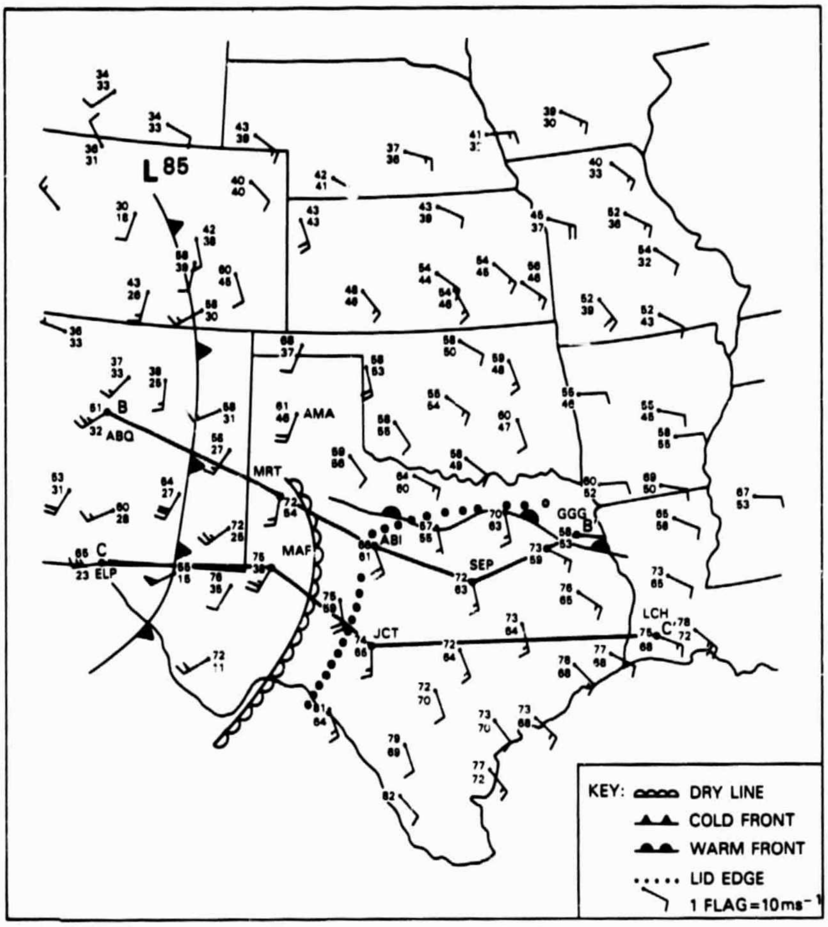


Figure 9. The 1800 GMT surface hourly analysis for 10 April 1979. Temperatures and dew points in (^{o}F) are plotted next to each surface station. Wind barbs have units of m s^{-1} (one flag = 10 m s^{-1}). Lines B-B′ and C-C′ refer to cross section analyses in Figs. 10 and 11.

most of the domain; and (3) there is a strong moisture discontinuity (dryline) in Texas (which we will show) influences the results of the vector differences between the wind fields. For these reasons, the 10 April case can also be used to compare the impact of CMV on SESAME wind fields for nonhomogeneous versus the more homgeneous air mass conditions for the CMV set derived for the 9 May case study.

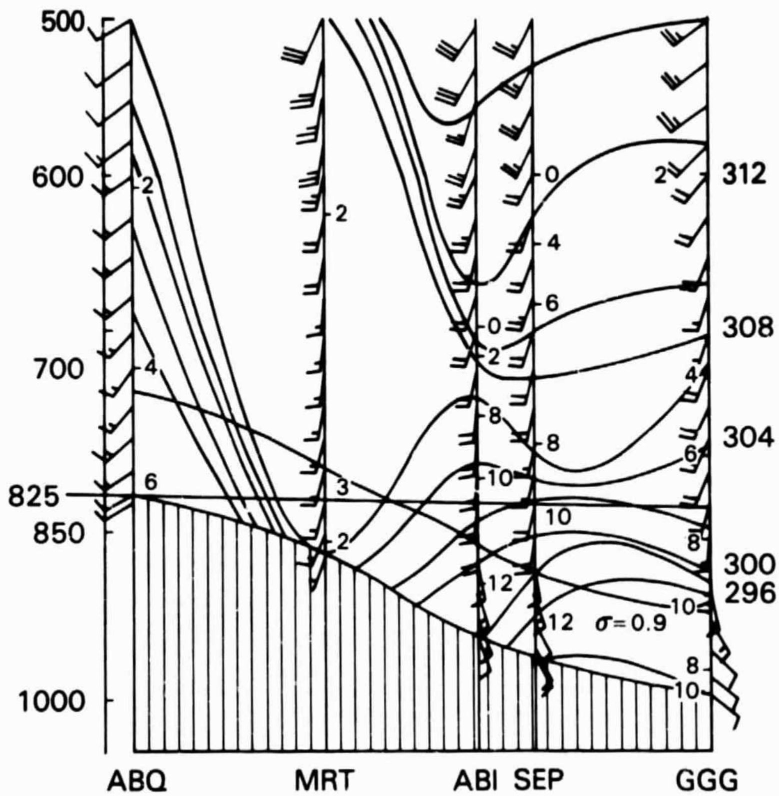


Figure 10. Vertical cross section from Albuquerque (ABQ), NM to Longview (GGG), TX along a sequence of stations B-B′ in Fig. 9 for 1800 GMT 10 April 1979. Solid lines correspond to isentropes (°K), single and double digit numbers refer to mixing ratios (g kg^{-1}), and one flag (✓)=10 m s^{-1}).

b. Results of the evaluation of the CMV data set

Fig. 12 shows vector differences between combined winds and SESAME winds for (a) CMV arbitrarily assigned to 825 mb, (b) CMV interpolated to 825 mb, (c) CMV arbitrarily assigned to σ=0.9, and (d) CMV interpolated to σ=0.9. Arbitrary assignment of CMV to 825 mb (Fig. 12a) produces large vector differences of 7 m s^{-1} and 6 m s^{-1} in eastern Texas and New Mexico, respectively. CMV are improperly assigned too high at 825 mb east of ABI

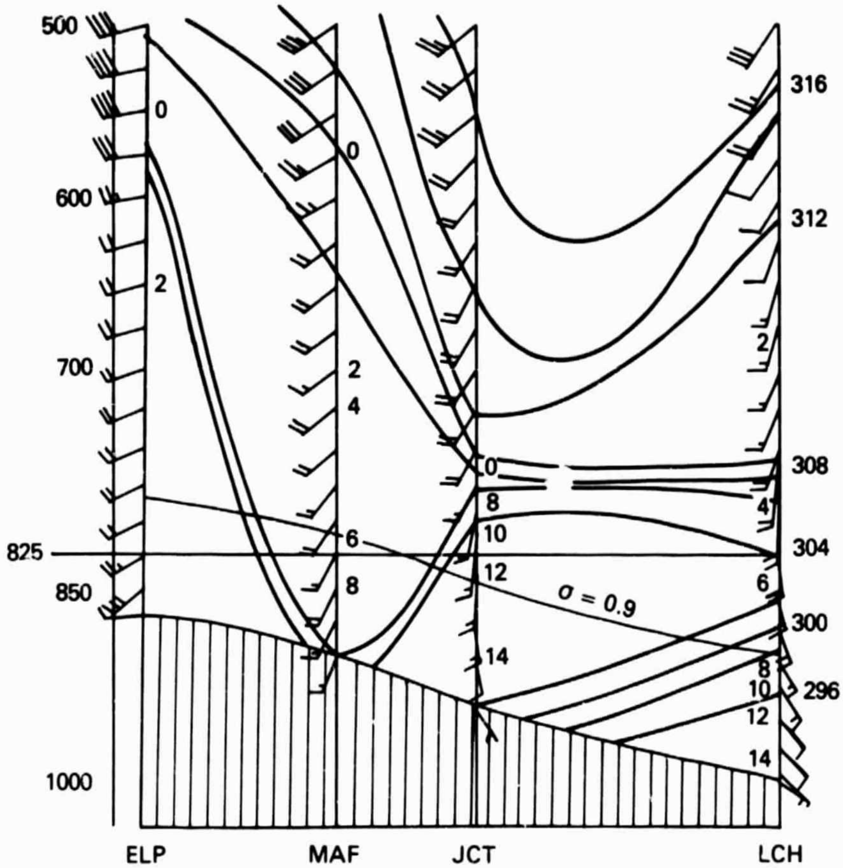


Figure 11. Vertical cross section from El Paso (ELP), TX to Lake Charles (LCH), LA along a sequence of stations C-C' in Fig. 9 for 1800 GMT 10 April 1979. Solid lines correspond to isentropes (^{o}K), single and double digit numbers refer to mixing ratios (g kg^{-1}), and one flag (✓)=10 m s^{-1}.

in the presence of vertical wind shear (Figs. 10, 11, and 13). In eastern Texas, the vertical wind field is highly variable between the surface and 825 mb. The vertically-averaged shear between 775-875 mb is 1.8 m s^{-1} 25 mb^{-1} and 1.0 m s^{-1} 25 mb^{-1} in the u and v components, respectively. By assigning the 900-940 mb level CMW there to 825 mb (see Fig. 13), wind speeds are decreased and directions are made more south-southeasterly in direction in this area. These cloud tracers have lower cloud bases than their counterparts west of ABI where the air is drier and the lifting condensation level higher. In New Mexico, CMV are being improperly assigned too low at 825 mb as their stronger southwesterly winds have increased the overall wind field by 5 m s^{-1}. Although Fig. 13 shows cloud bases at 700 mb in New Mexico, the actual values may be even higher due to the existence of the very dry air through the lower 200-300 mb of the atmosphere. An accurate interpolation of cloud bases is difficult to achieve there because of sparse rawinsonde data west of MRT and the necessity to horizontally interpolate reported cloud bases across a moisture discontinuity (dryline) in western Texas. In the middle of the analysis domain, between MAF and JCT, the arbitrary assignment of CMV (Fig. 12a) has little impact on the rawinsonde winds because of smaller vertical wind shears (1 m s^{-1} 25 mb^{-1}) and because the 825 mb assignment level is very close to the CMV cloud bases. The dryline, which borders this area, has an important effect on the overall wind field as determined by using the CMV. The CMV are higher than 825 mb west of the dryline, and consequently, they tend to increase the u component of the wind in the presence of positive vertical wind shear. Farther east of the dryline, CMV are lower in height than 825 mb and they tend to decrease the u component of the wind.

Interpolation of CMV to 825 mb gives somewhat smaller vector differences than for arbitrary assignment (Fig. 12b) in eastern Texas and New Mexico where the cloud bases are furthest from the 825 mb level (Fig. 13). The major change appears in eastern Texas where vector differences are 3 to 4 m s^{-1} for the interpolated wind set as compared to 6 to 7 m s^{-1} for the arbitrarily assigned CMV analysis. Vector differences

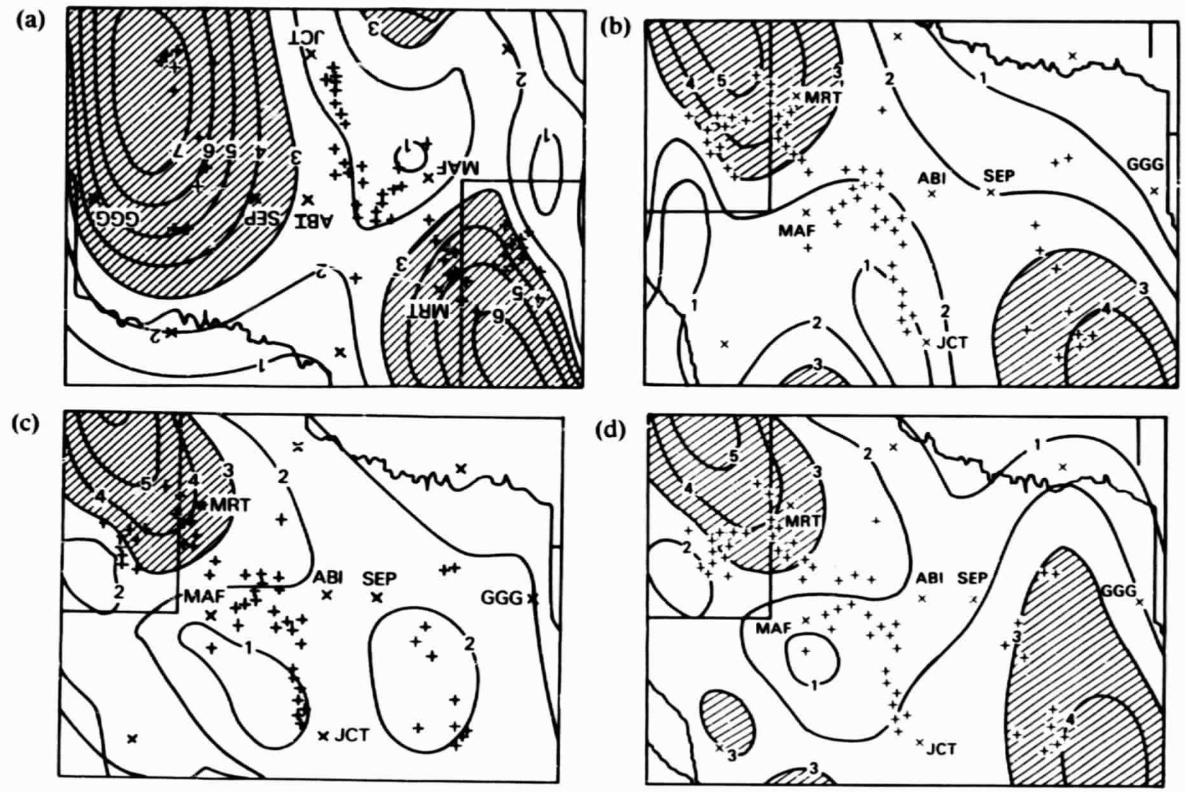


Figure 12. Magnitude of the vector differences in wind ($m\ s^{-1}$) between combined (SESAME and CMV) winds and SESAME winds at 1800 GMT 10 April 1979 for CMV (a) arbitrarily assigned to 825 mb, (b) interpolated to 825 mb, (c) arbitrarily assigned to σ=0.9, and (d) interpolated to σ=0.9. Vector differences $\geq 3\ m\ s^{-1}$ are shaded. The (+) markers are rawindsonde data locations.

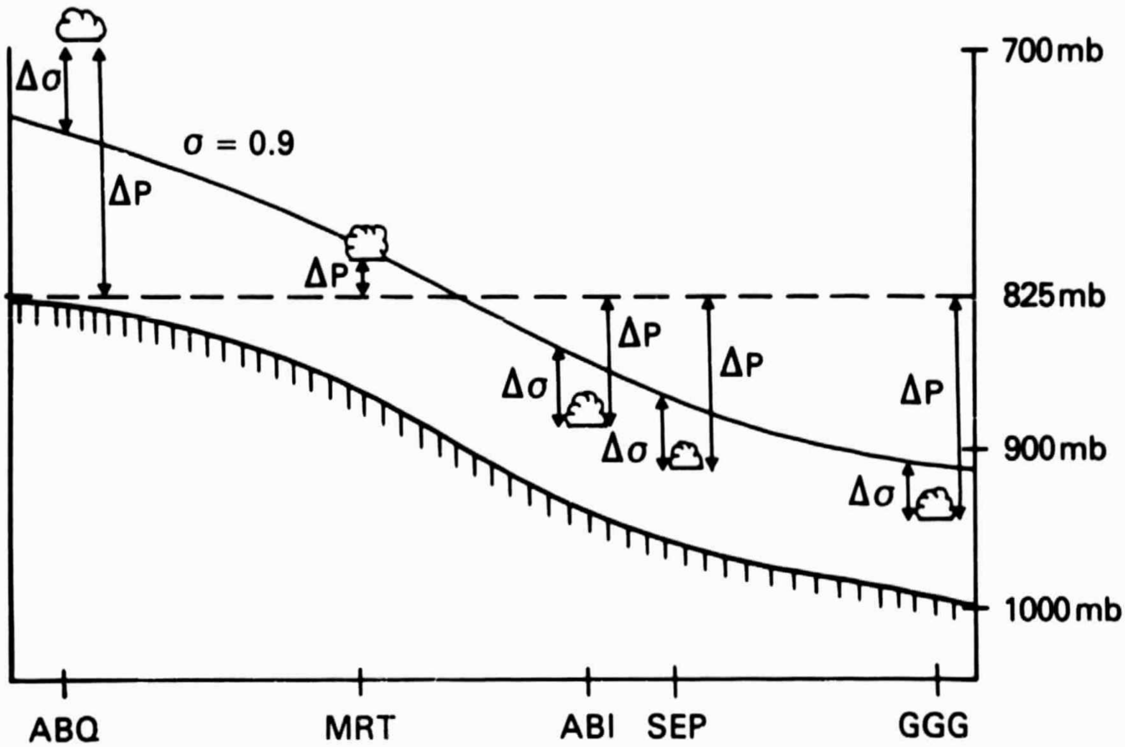


Figure 13. Schematic diagram showing the location of cloud tracers (☁) relative to the p=825 mb and σ=0.9 coordinate surfaces at selected regional scale rawinsonde stations for 1800 GMT 10 April 1979.

remain above 3 m s^{-1} for the interpolated wind set because either the vertical wind shear used for the interpolation is not fully representative of the shear which surrounds the clouds, or the CMV between the radiosonde sites (especially in south central Texas) are in fact adding coherent information to the analysis which could not be resolved by the radiosonde network alone. The large vector differences in New Mexico are likely the result of less certain cloud base levels and problems related to interpolation across a dryline within a data sparse area. Most of the latter clouds are located above 775 mb, and therefore exist in a different vertical wind shear environment.

Arbitrary assignment of CMV to σ=0.9 (Fig. 12c) results in the smallest vector differences overall. Cloud bases increase in elevation and apparently parallel the σ=0.9 surface across eastern Texas. The σ=0.9 surface is a better choice of level assignment than 825 mb for this reason, just as in the 9 May case. The remaining vector differences $\geq$3 m s^{-1} in New Mexico can be explained on the basis of CMV which are still assigned too low. The cloud base levels rise above the σ=0.9 surface to the west of the dryline. This behavior is consistent with the presence of much drier air, and hence, higher condensation levels over New Mexico. Strong moisture gradients evidently impose an upper limit on the usefulness of the sigma coordinate system for CMV level assignment over a large analysis domain. This example indicates that the selection of σ levels appropriate to different air mass regimes could possibly increase the effectiveness of the sigma coordinate system for dryline cases.

A comparison between arbitrary assignment (Fig. 12c) and interpolation (Fig. 12d) of CMV to σ=0.9 shows small differences between the two cases except in southeast Texas. The limitations in the vertical interpolation routine prevent distinct differences between arbitrary assignment and interpolation of CMV. The results in southeast Texas depend largely upon the vertical wind shear calculated between σ=.875 and σ=.950 under highly variable wind conditions. Perhaps the most consistent feature for all four assignment cases is the maximum in vector differences in New Mexico. This feature persists for both 825 mb and σ=0.9 probably due, in part, to the existence of CMV above both levels under weak vertical wind shear conditions. However, the magnitude of the vector differences also remains large because of a suspected sampling problem in the rawinsonde data. A moderate horizontal gradient of the u component exists across New Mexico in response to an upper level jet streak (see ELP in Fig. 11). Consistently large vector differences at more than one level could be either a reflection of increased error in the rawinsonde measurement of the wind at a point within an area of large horizontal wind shear, or possibly a reflection that satellite winds are adding a consistent information signal to the combined wind field.

Fig. 14 shows 825 mb divergence fields derived from (a) SESAME winds, (b) SESAME winds and arbitrarily assigned (noninterpolated) CMV, and (c) SESAME winds and interpolated CMV. The 825 mb SESAME winds are most strongly convergent over New Mexico and northern Texas. This convergence field is the result of the confluence of strong southwesterly winds from the area around ELP with weaker south-southwesterly winds near the dryline. The arbitrary assignment of CMV to 825 mb (Fig. 14b) retains a broadly convergent wind field in west and central Texas and extends convergence into southwest Texas, but reduces the convergence values over New Mexico and produces divergence in eastern Texas. The divergence in eastern Texas results from the addition of relatively weak southeasterly CMV to a faster southwesterly wind field near GGG (Fig. 2). The convergence in west Texas results from the confluence of the southeasterly flow over eastern Texas with the southwesterly flow over New Mexico and western Texas as displayed by the CMV in Fig. 2.

The interpolation of CMV to 825 mb (Fig. 14c) tends to create a tighter gradient of convergence across central Texas and to reduce divergence further east, compared to Fig. 14b. The interpolated field is similar to the arbitrarily assigned field across western Texas where wind shears are weak and the cloud motions are nearly at the 825 mb level. The major difference between these two fields is in eastern Texas where wind

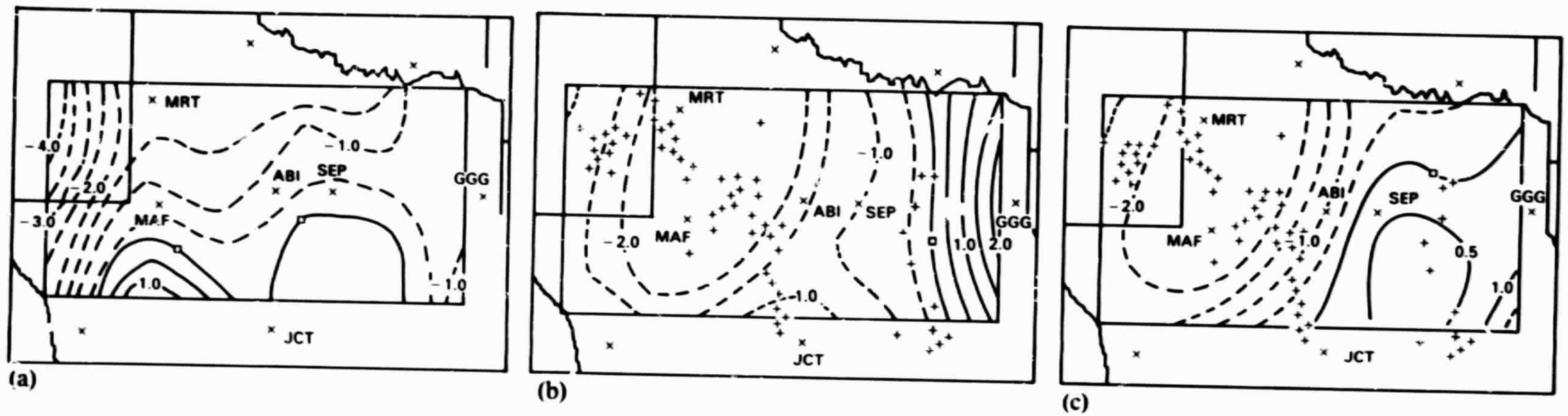


Figure 14. 825 mb divergence fields (units= x 10^{-5} s^{-1}) for 1800 GMT 10 April 1979 derived from (a) SESAME winds only, (b) combined SESAME winds and arbitrarily assigned (noninterpolated) CMV, and (c) combined SESAME winds and interpolated CMV. Solid lines are contours of divergence; dashed lines are contours of convergence.

shears are variable and vector differences in the wind are larger for arbitrary assignment than interpolated assignment.

Fig. 15 shows divergence fields derived from the various analyses at the σ=0.9 level. A comparison between 825 mb SESAME divergence (Fig. 14a) and σ=0.9 SESAME divergence (Fig. 15a) shows similar patterns in the divergence fields. The arbitrary assignment of CMV to σ=0.9 (Fig. 15b) retains the overall convergent field found in the SESAME analysis (Fig. 15a) although the maximum value of convergence (-2×10^{-5} s^{-1}) shifts southwestward from north central Texas. The interpolation of CMV to σ=0.9 (Fig. 15c) also retains a convergent field in western Texas. The major difference in the divergence fields is that the inclusion of the CMV increases the gradient in divergence across eastern and southern Texas. The σ=0.9 arbitrarily combined and interpolated analyses are similar in western Texas where vertical wind shears are weak and have little impact on the resultant divergence. A consistent signal does not appear in eastern Texas where horizontal and vertical wind shears are highly variable and where cloud base levels and the σ=0.9 surface are widely separated in the vertical.

Without an independent measure of the wind field, it is impossible to determine the extent to which the CMV are adding realistic mesoscale detail to the pressure and sigma level divergence fields. Nevertheless, it appears that the CMV at 825 mb in the data void regions in central Texas are producing a more coherent signal in the divergence fields, with tighter gradients in a region in which critical changes are occurring that contributes to the severe weather outbreaks after 1800 GMT. The enhancement of the convergence-divergence couplet in Texas occurs immediately along the axis of a developing low-level jet (LLJ) (Kocin <u>et</u>

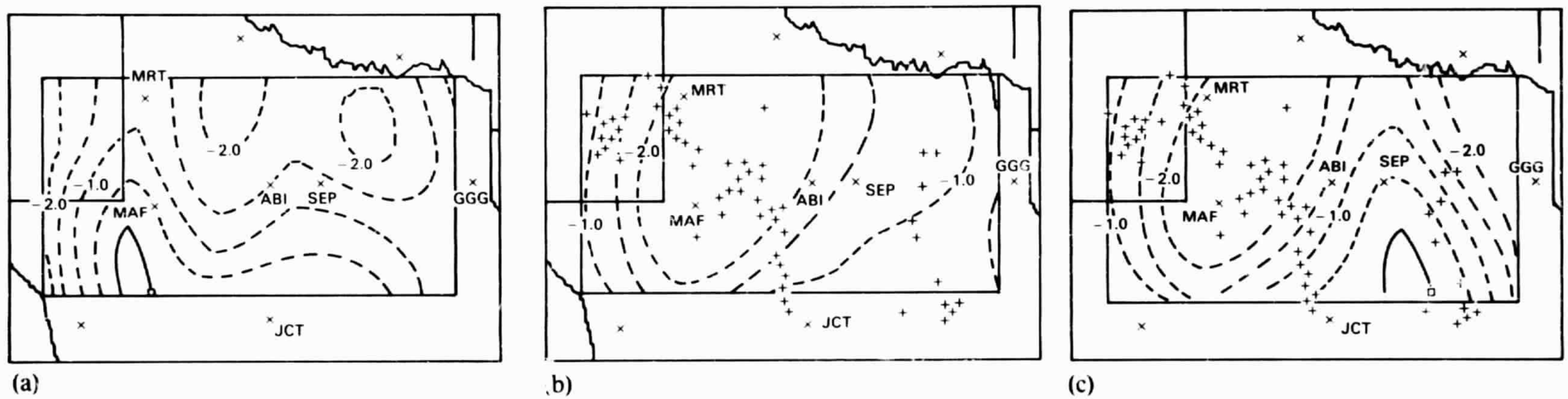


Figure 15. σ=0.9 divergence fields (units= x 10^{-5} s^{-1}) for 1800 GMT 10 April 1979 from (a) SESAME winds only, (b) combined SESAME winds and arbitrarily assigned (noninterpolated) CMV, and (c) combined SESAME winds and interpolated CMV. Solid lines are contours of divergence; dashed lines are contours of convergence.

al., 1982; Moore and Fuelberg, 1981), which increases the moisture transport toward the region in which the tornado-producing storms develop. The divergence which is resolved with the CMV at 825 mb in southeast Texas is located in the entrance region of the narrow stream of air accelerating into northern Texas at 1800 GMT (Fig. 16). The CMV-enhanced convergence field along the dryline is located in the exit region of the developing LLJ where it meets the dry southwesterly air stream originating in New Mexico. Subtle differences do exist in the divergence fields, as just described, between the various assignment methods and surfaces. The greatest differences appear between the pressure and sigma analyses when conducting an arbitrary assignment (compare Figs. 14b and 15b). Recall that very little such differences appeared in the 9 May case, which was characterized by weaker vertical wind shears and more homogeneous conditions. Despite this, the present case demonstrates that the major difference is between the rawinsonde fields and the CMV-enhanced fields.

A similar exercise applied to relative vorticity fields shows that there is less variation among the relative vorticity fields produced by the various assignment methods than among the divergence fields. The relative vorticity fields produced by arbitrarily assigning the CMV (Figs. 17b, 18b) and also those produced by vertical interpolation (Figs. 17c, 18c) show an alternating pattern of maximum and minimum relative vorticity across central and western Texas, which is non-existent in the SESAME fields (Figs. 17a, 18a). The differences in structure which exist among the vorticity fields reflect differences related to basic differences in the vector wind field. Regardless of whatever assignment method and surface is used, the CMV appear to be adding a more coherent signal in the relative vorticity fields by producing a pattern consistent with the location of the jets in western and southeastern Texas.

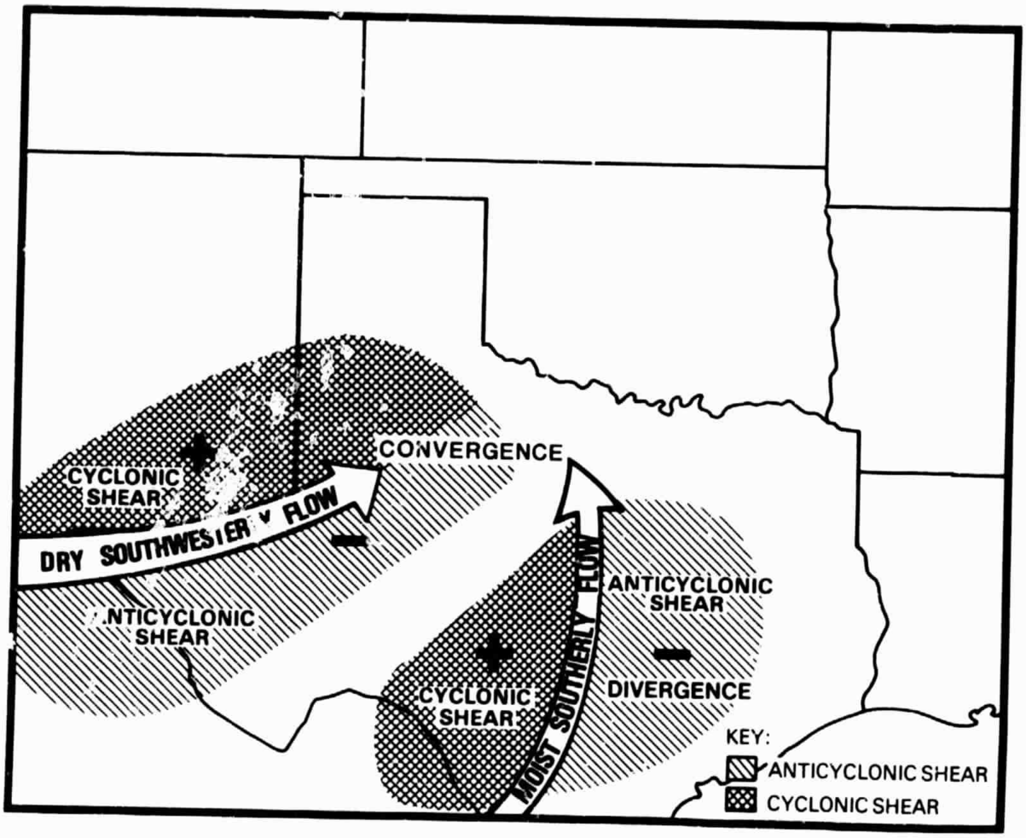
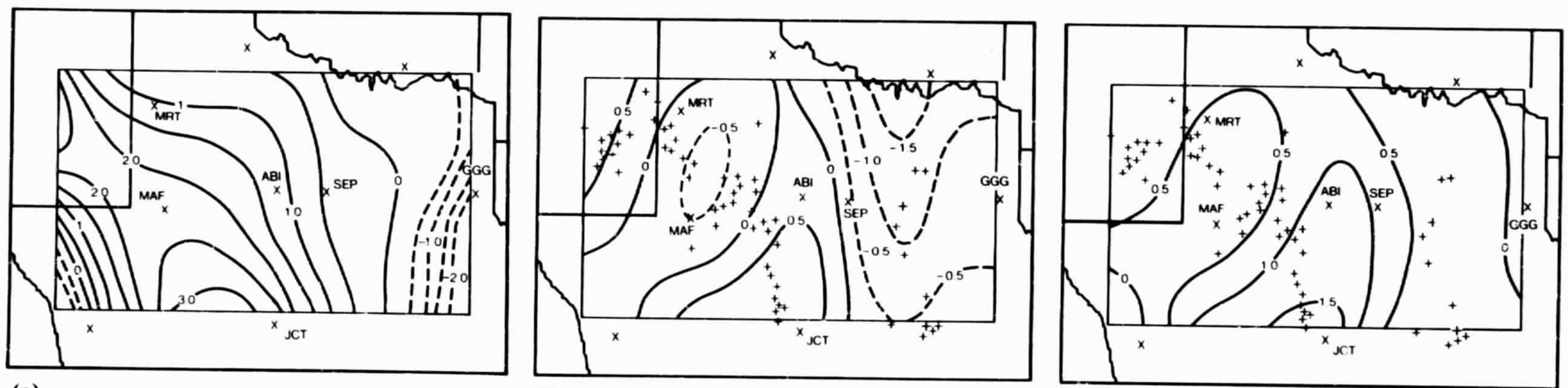


Figure 16. Schematic diagram showing the location of divergence/convergence and relative maximums and minimums in relative vorticity consistent with lower level accelerating flows across Texas for 1800 GMT 10 April 1979.



(a) (b) (c)

Figure 17. 825 mb relative vorticity fields (units = x 10^{-5} s^{-1}) for 1800 GMT 10 April 1979 derived from (a) SESAME winds only, (b) combined SESAME winds and arbitrarily assigned (noninterpolated) CMV, and (c) combined SESAME winds and interpolated CMV. Solid lines are contours of positive (cyclonic) relative vorticity; dashed lines are contours of negative (anticyclonic) relative vorticity.

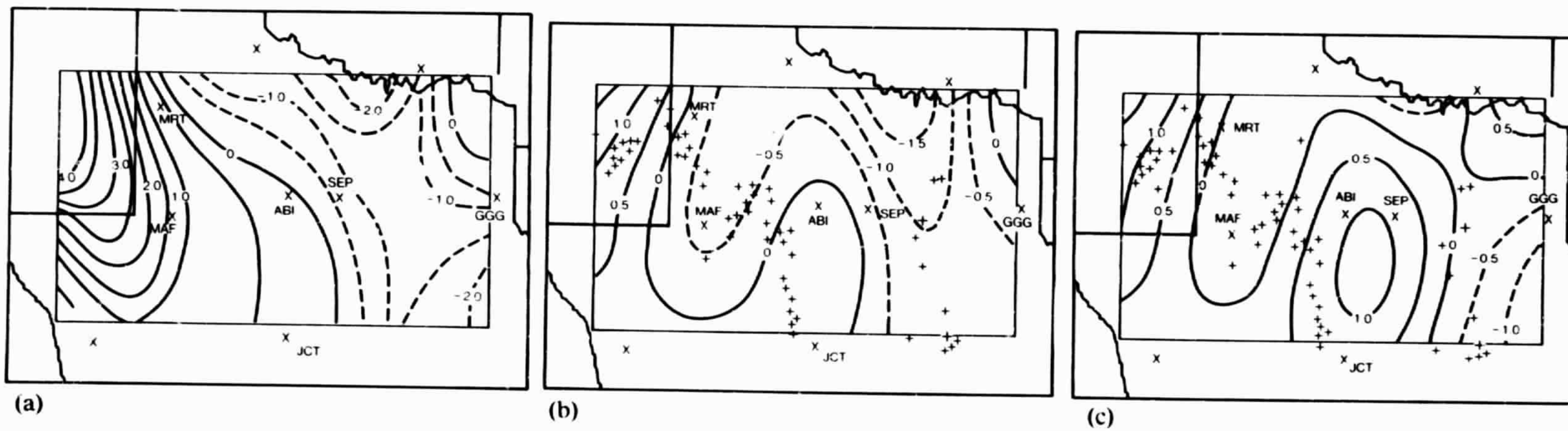


Figure 18. σ=0.9 relative vorticity fields (units = x 10^{-5} s^{-1}) for 1800 GMT 10 April 1979 derived from (a) SESAME winds only, (b) combined SESAME winds and arbitrarily assigned (noninterpolated) CMV, and (c) combined SESAME winds and interpolated CMV. Solid lines are contours of positive (cyclonic) relative vorticity; dashed lines are contours of negative (anticyclonic) relative vorticity.

6. Summary and conclusions

The "typical" practice of assigning low level CMV to a single level in pressure (p) coordinates for objective analysis is complicated by limitations in methods of cloud height specification and a lack of understanding of cloud motion/environmental wind relationships. The majority of researchers have identified their cloud motion vectors (CMV) as low level with cloud top temperature data from infrared satellite imagery, and have determined cloud base levels using surface reports and soundings. CMV are customarily assumed to approximate the environmental wind at cloud base level. An analysis of the results acquired from these "typical" procedures is required for various meteorological conditions, for otherwise these methods will always be described as arbitrary.

A straightforward examination of the validity of these customary methods is conducted by analyzing the impact of CMV arbitrarily assigned to single coordinate surfaces. The 825 mb and $\sigma=0.9$ levels are chosen as "typical" levels for the CMV in two SESAME cases. Vertical interpolation of CMV to these levels is also accomplished to test the ability of interpolation to account for vertical wind shear between cloud base level and the selected p or σ surfaces. Vector differences in wind between combined (SESAME rawinsonde winds and CMV) winds and SESAME-only winds, and divergence and relative vorticity fields derived from SESAME winds and combined winds are used to study the impact of cloud motions on SESAME wind fields. The vector difference fields are explained in terms of the effects of wind and moisture gradients.

The selected case studies (9 May and 10 April 1979) are chosen for their different characteristics. The 9 May case has more uniform cloud motion data distribution, weaker vertical wind shears, and more homogeneous air mass conditions than the 10 April case.

The results from both case studies indicate that:

(1) The arbitrary assignment of CMV to a single p level produces vector differences in the wind as large as 7 m s^{-1} between the combined winds and SESAME winds. Differences are usually largest near moisture discontinuities, horizontal gradients of the wind, and within areas of moderate-to-strong vertical wind shear.

(2) When estimates of vertical wind shear are not available, then <u>arbitrary assignment</u> to σ will reduce the vector differences, and is thus preferred over arbitrary assignment to p. The variation of cloud bases across sloping terrain apparently parallels closely the slope of a σ surface within homogeneous air masses. This acts to minimize the impact of vertical wind shear between cloud base levels and the assigned level. In a situation where horizontal moisture gradients exist, arbitrary assignment of CMV to σ could possibly be improved by selecting σ levels appropriate to different air mass regimes. However, this refinemnt will lead to fewer number of wind reports at any one level, increasing the clustered nature of this non-conventional data set and thus possibly reducing its impact on the wind analysis over a large domain.

(3) When estimates of vertical wind shear are availabe from a special data set, <u>interpolation</u> of CMV to either p or σ is acceptable for combined wind field analyses. The interpolation of CMV to 825 mb produces smaller vector differences than arbitrary assignment to that level. The advantage of interpolation is in accounting for the large vertical wind shear over a significant depth of the lower troposphere between cloud base levels and

the level of the coordinate surface. Interpolation of CMV to σ=0.9 did not produce smaller vector differences than arbitrary assignment to that level. There was no advantage in interpolation to σ because cloud base levels were very close to σ=0.9, especially for the 9 May case. Interpolation through a small $\Delta\sigma$ is severely impacted by limitations in the interpolation routine.

(4) The addition of CMV to SESAME winds impacts the rawinsonde divergence and relative vorticity fields, whether the CMV are interpolated to p or σ. CMV appear to add actual physical data to the basic wind analyses, regardless of the method of assignment, although subtle differences in the divergence fields do exist between the various CMV analyses.

This work represents only an initial step in defining how limits upon satellite cloud motions have the potential to be effectively used to add information to basic wind analyses. The next step should be to find a method to determine the optimum value of the specified coordinate system as a function of air mass regime. In doing so, the limitations of the σ system can be determined (already seen to an extent in the 10 April case across the dryline where σ does not account for moisture gradients). The use of stereo height data or the VAS slice method (Menzel et al., 1983) to determine more accurate cloud bases, and an examination of new methods for determining vertical wind shear, should improve our ability to acquire accurate interpolated fields. However, an improvement in accuracy of cloud height determination does not solve the problem of interpolating the data vertically to a single coordinate level for numerical analysis and initialization purposes. Further examination is needed in this area.

The use of timely 3 hourly (SESAME-type) data seemed critical for (a) the establishment of a link between computed differences in various quantities and horizontal and vertical gradients in wind and moisture fields and for (b) acquiring an estimate of vertical wind shear necessary for interpolation of winds to another level. In practice, where special data are not available, arbitrary assignment to sigma surfaces is preferred, or otherwise model output will have to be used as the basis for providing the needed vertical wind shear conditions at times in between rawinsonde data collection.

This work shows that before CMV data can be assimilated back into a mesoscale model to examine their impact on the model forecast fields, caution must be exercised to assure that systematic errors resulting from improper level assignment of the CMV in the presence of vertical wind shear and horizontal moisture gradients are minimized. These precautions are most important in highly baroclinic situations over land. Our results are not inconsistent with the fact that oceanic cumulus are tracked routinely to provide needed data over data-sparse regions for the initialization of larger-scale models, since the effects of shear and moisture gradients are much smaller and it has been shown that in these situations, cumulus usually move with the winds at cloud base level.

APPENDIX

A. Analysis techniques

A computer interactive Barnes interpolation scheme developed by Koch et al. (1983) is used to provide objective analysis input parameters and to display indicators of analysis quality of non-uniformly distributed satellite data sets. This scheme defines two analysis areas in an attempt to acquire a uniformly reliable analysis (see Figs. A1 and A2). The larger "data area" is chosen to include rawinsonde wind data outside the area of CMV to minimize boundary problems due to extrapolation of data values to the data-sparse edge of the analysis grid. The inner box is the "grid display" area which represents that part of the gridded "data area" which is displayed as the most reliable analysis. Data spacing and grid spacing are objectively determined. The data spacing (Δn) corresponds to the Δn of the regional scale SESAME data rather than that of the CMV because we are examining the regional scale impact of the smaller scale nonuniformly distributed CMV upon the rawinsonde wind field. The values of the data spacing used are $\Delta n = 2.7^{\circ}$ latitude for 9 May and $\Delta n = 2.0^{\circ}$ latitude for 10 April. The weights of the Barnes low pass filter are determined solely by these data spacings resulting in a 37% (1/e) response at the $2\Delta n$ scale. A grid spacing is computed from the Δn value to insure proper representation of resolvable features. Two passes through the data are made to achieve sufficient convergence of the analyzed fields to the observed fields.

"Interpolation difference" maps generated by this interactive scheme permit determination of the quality of the objective analyses. These should not be confused with the "difference maps" (combined minus SESAME analyses) discussed earlier. Interpolation difference maps are objective analyses of the differences between the grid point wind values (back interpolated to the data locations) and the observed wind fields. Figs. A3 and A4 show interpolation differences for the 825 mb combined (SESAME and CMV) wind data on 9 May and 10 April, respectively. Most differences are less than 0.5 m s^{-1} and are considerably less than the estimated rmse in rawinsonde 700 mb winds of 2.5 m s^{-1} (Fuelberg, 1974). Thus, the analyses are reliable throughout most of the grid display areas. Extrapolation of values from the rawinsonde stations to grid points in data-void areas beyond the grid display area on 10 April (Fig. A2) causes the interpolation error in southwest Texas (Fig. A4) which results in the largest difference of 1.2 m s^{-1} south of Marfa (MRF), Texas. This interpolation difference, although still less than the observed error, would have required caution in interpreting results there. Fortunately, this small area is not of primary concern in this paper.

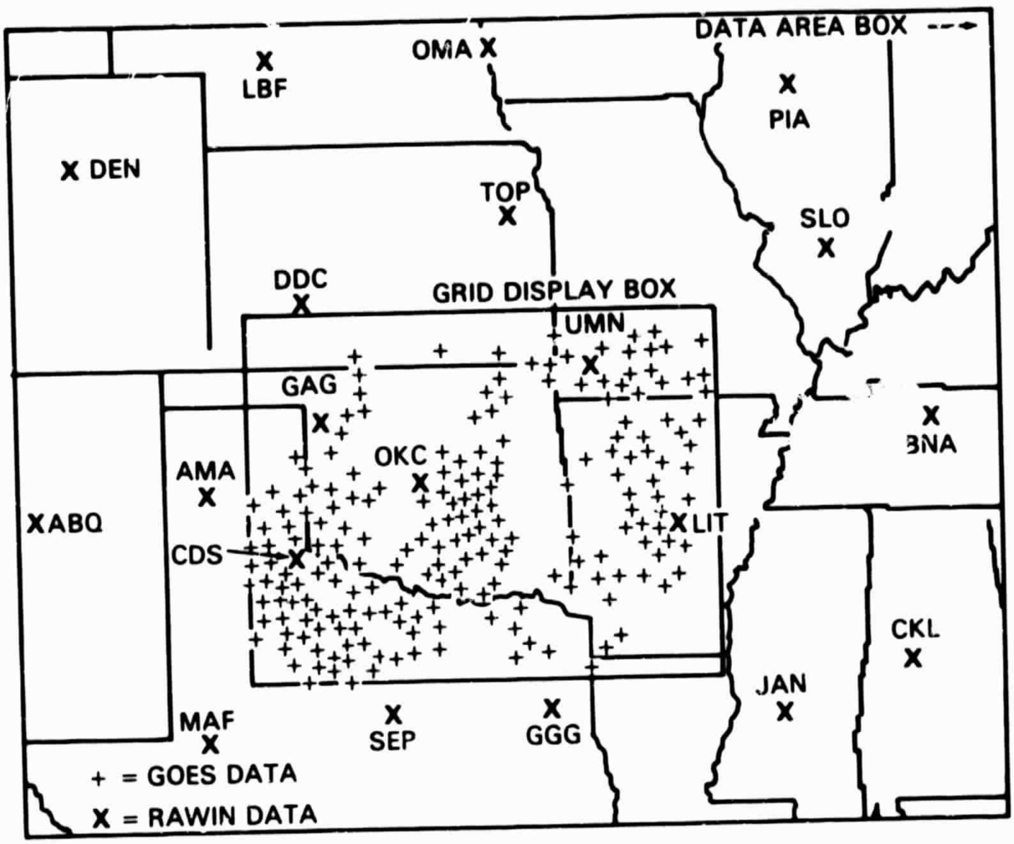


Figure A1. Data and grid display areas used in the Barnes interpolation scheme for 9 May 1979. The locations of rawinsonde wind data and cloud motions are denoted by (x) and (+) respectively.

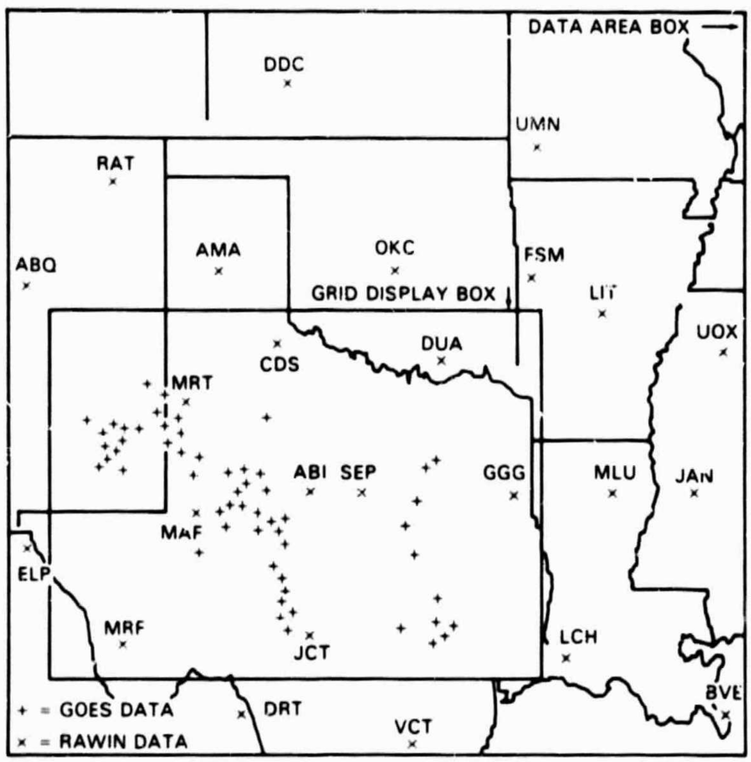


Figure A2. Same as Fig. A1 except for 10 April 1979.

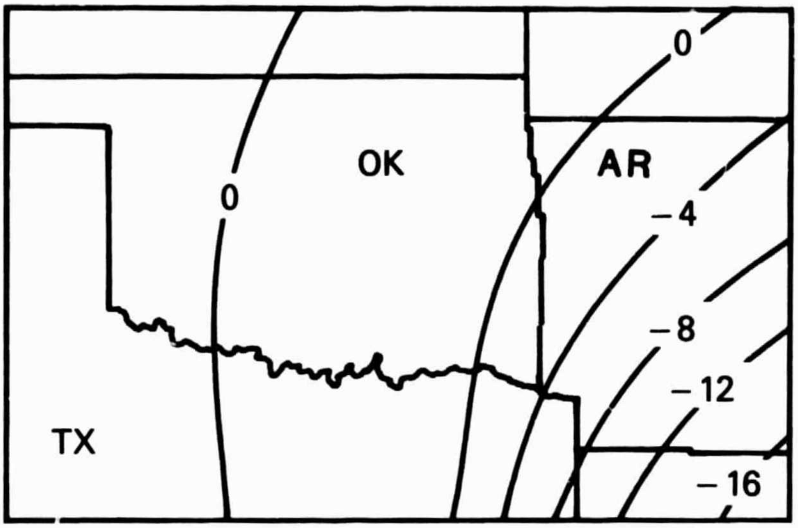


Figure A3. Interpolation difference map of combined rawinsonde winds and CMV data for 9 May 1979. Units: x 10^{-1} m s^{-1}.

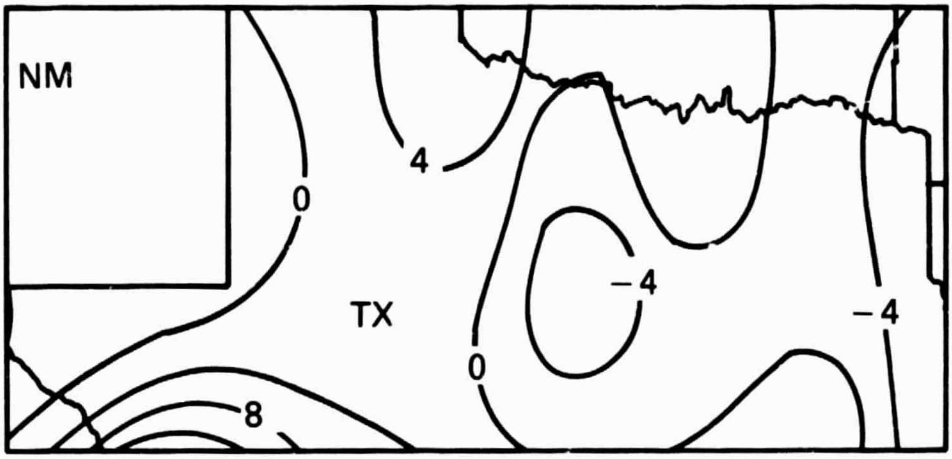


Figure A4. Same as Fig. A3 except for 10 April 1979.

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