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Cirrus Cloud Development in a Mobile Upper Tropospheric Trough: The November 26th FIRE Cirrus Case Study

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1. Introduction

The period from 18 UTC 26 November 1991 to roughly 23 UTC 26 November 1991 is one of the study periods of the FIRE II field campaign. The middle and upper tropospheric cloud data that was collected during this time has allowed FIRE scientists to learn a great deal about the detailed structure, microphysics and radiative characteristics of the mid latitude cirrus that occurred during that time. Modeling studies that range from the microphysical (Mitchell et al., this issue) to the mesoscale (Jensen et al. , this issue) are now underway attempting to piece the detailed knowledge of this cloud system into a coherent picture of the atmospheric processes important to cirrus cloud development and maintenance. An important component of the modeling work, ether as an input parameter in the case of cloud-scale models, or as ouput in the case of meso and larger scale models, is the large scale forcing of the cloud system. By forcing we mean the synoptic scale vertical motions and moisture budget that initially send air parcels ascending and supply the water vapor to allow condensation during ascent. Defining this forcing from the synoptic scale to the cloud scale is one of the stated scientific objectives of the FIRE program.

from the standpoint of model validation, it is also necessary that the vertical motions and large scale moisture budget of the case studies be derived from observations. We consider it important that the models used to simulate the observed cloud fields begin with the correct dynamics and that the dynamics be in the right place for the right reasons.

2. Data, Data Processing and Objective Analysis

The FIRE Cirrus hub in Coffeyville, Kansas was uniquely positioned near the center of a large observational array of wind profilers and radiosonde sites. Spacing between wind profilers in this region was on the order of 175 km. This spacing increased to approximately 400 km away from the hexagonal array of wind profilers in central Oklahoma and southern Kansas. The wind profilers provided six minute radial velocities for each of their three beams (two oblique and one vertical) from 500m above ground level to 16.25 km above ground level with vertical resolution of 250m up to approximately 7 km and 1 km resolution to 16.25 km. The six-minute radial velocity data were processed using a mode filter and consensus averaging. The data were averaged to the top of each hour. The consensus average required that at least four of the ten six minute observations in a sixty minute period be within a predefined range. Otherwise the data were flagged as missing.

The radiosonde data consisted of five Chain Link Atmospheric Sounding System (CLASS) sites as well as supplemental radiosonde data provided by the conventional National Weather Service radiosonde network. During this particular cloud event the 15 NWS radiosonde sites nearest Coffeyville and the CLASS sites were launching radiosondes at three hour intervals, while the remainder of the radiosonde network in the western 2/3 of nation was launching balloons at six hour intervals. The raw NWS radiosonde data were processed at full vertical resolution using techniques designed by Starr and Lare (personal communication) and the raw CLASS data were filtered for erroneous data by the National Center for Atmospheric Research.

Combining the wind profiler and radiosonde datasets into a single product is necessary for further analysis. Both networks have a horizontal resolution that is very coarse relative to most mesoscale models. However, the vertical resolution of both the rawinsonde and the wind profiler data and the temporal resolution of the wind profiler data is a significant advantage of the large-scale datasets collected during FIRE II.

In order to successfully combine the wind profilers and radiosonde datasets into a single product, we must account for the differences in the two observational platforms. The wind profilers provide a close approximation to true vertical and temporal averages over single vertical columns. The radiosonde data, on the other hand, represents point measurements spread over some finite flight period along a vertical column tilted upshear. In a spatially and temporally enhanced rawinsonde network both the flight time and the instrument drift become significant factors in accurate data analysis.

Since the wind profiler data exist at hourly intervals and 250 m vertical resolution, our goal is to generate regional analyses valid at the nominal radiosonde launch times with 250 m vertical resolution. We chose to retain physical height coordinates in this analysis since no information exists in the wind profiler data to map it unambiguously onto an alternate vertical coordinate. On the other hand, the radisonde data contain sufficient information to place it on any vertical coordinate we choose.

Since the wind profiler data reprsent true layer-mean quantities, the first step in the objective analysis process requires vertical averaging of the radiosonde data. For the radiosonde data, we average individual observations 125m above and below the nominal height level. This averaging is performed with all the radiosonde data components including the latitude, longitude and time of each measurement. A time series of vertically averaged data are created by combining several soundings from a given location into a time-height array. This time series is then used to linearly interpolate the data at each level to the nominal sounding time. The actual launches occur generally 30-60 minutes before the nominal time and, depending on the ascent rate, may last 1-2 hours. It is important to note here that each data level of the time-interpolated, vertically averaged sounding retains a similarly interpolated latitude and longitude. This method, which is similar to one described by Frankhauser (1969), effectively accounts for both the drift in the radiosonde during flight and also the time interval of the ascent. Thus, displacement of the observations in both space and time will not add error to the horizontal or temporal derivitives necessary for further analysis.

We combine the wind profiler and radiosonde winds at this stage into a single dataset that is mapped to a one degree latitude and longitude grid using a bilinear interpolation scheme described by Hiroshi (1978). This procedure is performed at each data level from sea level to 16 km.

Since no account has been taken of observational error or of observed meteorological signal below the temporal or spatial scale of the observing netwrok it is important that a filtering technique be applied. As shown recently by Davies-Jones (1993) and by Thiebaux and Pedder (1987), over-determined polynomial fitting techniques are able to smooth observational fields, effectively decreasing random uncertainty and maximizing the desired atmospheric signal. Therefore, after mapping the observations to the grid, each interior gridpoint is smoothed by fitting an over determined plane to the gridpoint in question and to 12 unsmoothed surrounding gridpoints using ordinary least squares regression techniques. The over-determined plane minimizes the sum of squared residuals between the analysis and observational values. The slope of this plane in horizontal space also defines the spatial derivatives of the quantity at the central gridpoint. This technique removes much of the random observational error and small scale atmospheric signal. What remains is a synoptic scale analysis with horizontal resolution of about 2.5 x 2.5 degrees.

In order to gauge the effectiveness of the objective analysis technique, we performed the

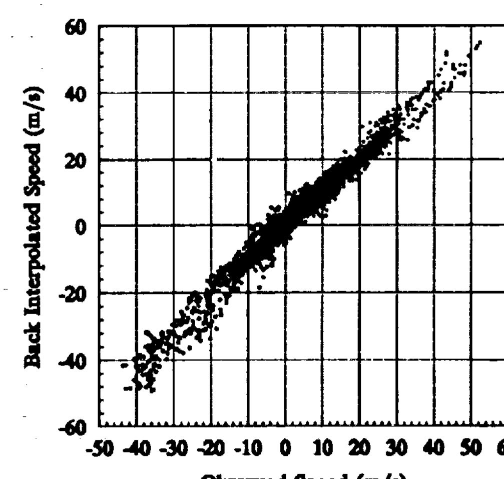

Figure 1. Scatter plot comparing the profiler observed horizontal wind components with the wind components interpolated to the profiler locations using the objective analysis techniques described in the text and data valid at 18 and 21 UTC 26 November 1991.

analysis as described above and then back interpolated the horizontal wind data at each analysis level to the wind profiler locations. The interpolated horizontal wind components were then compared with the observed horizontal wind components. The result is shown in Fig. 1. We find that the analysis technique closely fits the observations. The linear correspondence is strong in this plot with a correlation coefficient of 0.97. The root mean square difference between the observations and the objectively analyzed values is 2.5 m/s. Strauch et al. (1989) compared horizontal winds measured by two sets of orthogonal beams in a five beam profiler and found the RMS of the observations to be on the order of 2 m/s. Also, Benjamin (1991) reports that a similar comparison of the MAPS analyses and NGM analyses to radiosonde wind observations have an RMS difference of 4.0 and 5.1 m/s respectively. The objective analysis technique we describe fits the data more closely than MAPS or the NGM but still accounts for the RMS uncertainty in the observations.

3. The November 26th Case Study

The middle and upper tropospheric cloud band that was sampled during the local afternoon of 26 November 1991 was closely coupled to the synoptic scale dynamics embedded in the exit region of the strong northwesterly jet stream evident in Fig. 2. The jet extended from a ridge in the northwestern United States southeastward into the Texas Panhandle and a jet streak of 63 m/s was propagating southeastward near the flow inflection point in eastern Colorado. Immediately downstream of the jet core a difluent trough axis extended from eastern Texas northward into the Dakotas. Analysis of the Geopotential height field (not shown) shows that the trough axis had a well defined southeast-northwest tilt. This situation bears strong resemblance to a classic description of an upper jet-front system propagating through a synoptic scale baroclinic wave presented by Shapiro (1983) and Keyser and Shapiro (1987). This stage of development is marked by barotropic amplification through the tilt in the height field and by baroclinic amplificaition indicated by the weak cold advection in the northwesterly flow (Keyser and Shapiro, 1987). The amplification process is displayed quite markedly by examining the evolution of the dynamics between 18 UTC and 21 UTC. Fig. 3 shows a vertical east-west cross section of relative vorticity at 18 and 21 UTC. The cross section extends from the jet core in southeastern Colorado across the trough axis north of the Kansas-Oklahoma border and into the difluent zone in western Missouri. The vorticity pattern shows a region of cyclonic vorticity extending through the depth of the troposphere and situated from the jet core eastward into the difluent trough with maximum amplitude near 10 km. The vertical structure of the relative vorticity is nearly identical to that reported by Sanders (1988) in an observational study of mobile troughs in the upper westerlies. He found that upper tropospheric

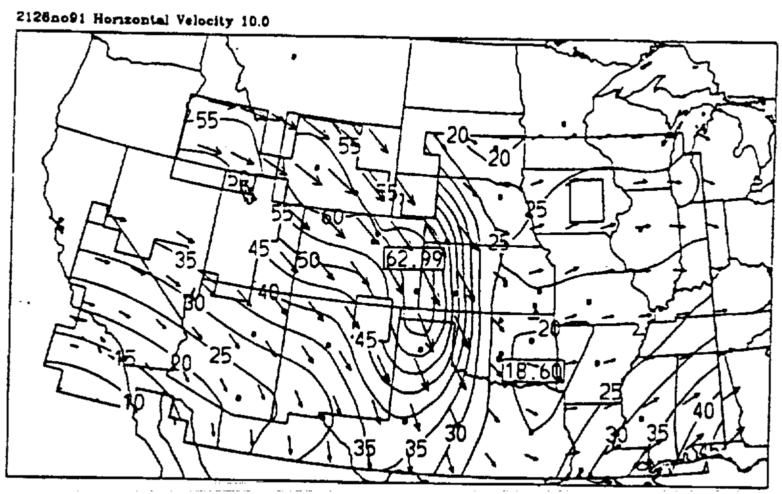

Fig. 2. 10 km horizontal winds at 21 UTC 26 November 1991. The contours are of wind speed in m/s and the vectors are compass direction with the length of the vector corresponding to the speed of the horizontal wind. The small squares within the analysis region represent the positions of radiosonde and wind profiler wind observations used in the objective analysis scheme .

mobile troughs tended to amplify preferentially leeward of the major topographic regimes in the northern Hemisphere and had length scales on the order of 2500 Km. Similarly, Whitaker and Barcilon (1992) argued from a theoretical basis that these mobile troughs with maximum amplitude in the upper troposphere tended to amplify under conditions of weak low-level baroclinicity, large low level static stability and large surface roughness.

The evolution of the vorticity pattern associated with the jet-trough system is clearly evident. The entire pattern appears to progress eastward during the three hour period while the amplitude of the disturbances changes very little in the middle and lower troposphere. However, a significant amplification of the disturbance occurs between 8.5 and 12 km.; the maximum vorticity increases from 15 to 19 /s in three hours. The negative vorticiity values in the flanking migratory ridges show little change aside from a eastward progression during the period.

The vertical velocity was calculated as a residual from the first law of thermodynamics assuming adiabatic flow. Results at 7.5 km are shown in Fig. 4. At 18 UTC weak rising motion is diagnosed in eastern Oklahoma and Kansas while relatively strong subsidence occurred in eastern New Mexico and west Texas. Amplification of the vertical motion pattern occurred by 21 UTC. The subsidence center had more than doubled in intensity and was oriented near the left front exit region of the advancing northwesterly jet streak. The region of rising motion in the difluent trough had also intensified, more than doubling in magnitude in eastern Kansas and northeastern Oklahoma. Cross sections of the adiabatic vertical velocity show a similar amplification of the vertical motion pattern through much of the troposphere between 18 and 21 UTC.

The cloud system extended from Nebraska to eastern Texas along and ahead of the strong horizontal shear associated with the advancing jet. Cirrus was first observed between 8 and 9 km over Coffeyville by cloud radar at approximately 18 UTC. The advancing cirrus quickly thickened to include the layer between 6 and 9 km. Bases descended to 2-3 km after 21 UTC while the cloud tops remained near 9 km. Reflectivities through the depth of the cloud system also increased after 21 UTC. As the strong subsidence zone moved over southeastern Kansas, skies cleared over Coffeyville after 23 UTC .

3. Conclusions and Future Work

The evolution of the cloud system extensively observed on 26 November can be seen as a response to vertical circulations associated with synoptic scale forcing. As the rapidly advancing jet streak passed the flow inflection point after 18 UTC, the system became predisposed to large scale amplification through the orientation of the trough axis and cold air advection. The strong gradient in velocity insured that parcels exiting the jet were strongly

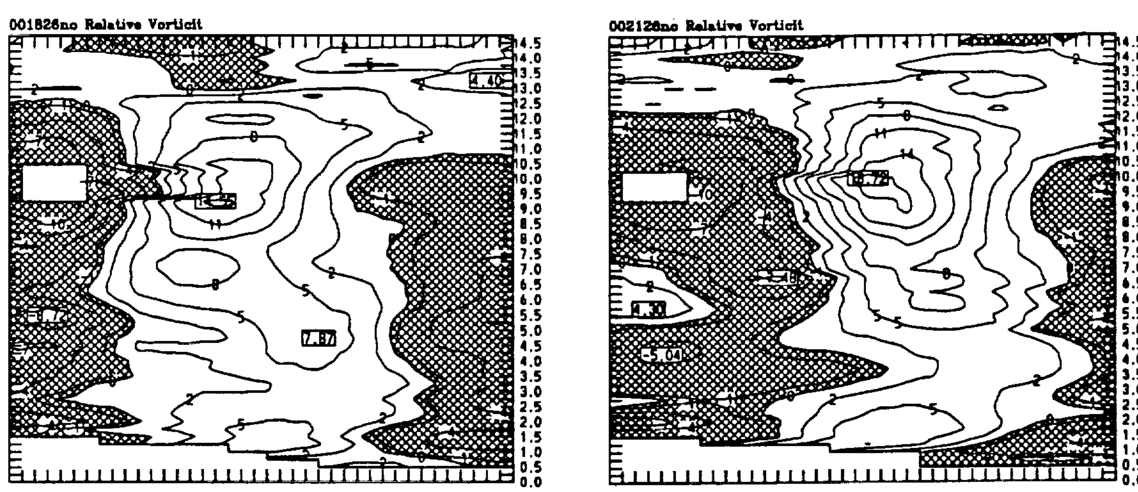

Fig. 3. Cross sections of the vertical component of the relative vorticity for a) 18 UTC 26 Nov 91 and b) 21 UTC 26 Nov 91. The cross sections extend in an east west line from south-central Colorado to southwestern Missouri. The location of Coffeyville, Kansas is marked with an arrow on each plot. Units are in 10^{-5} s^{-1} and negative values are shaded.

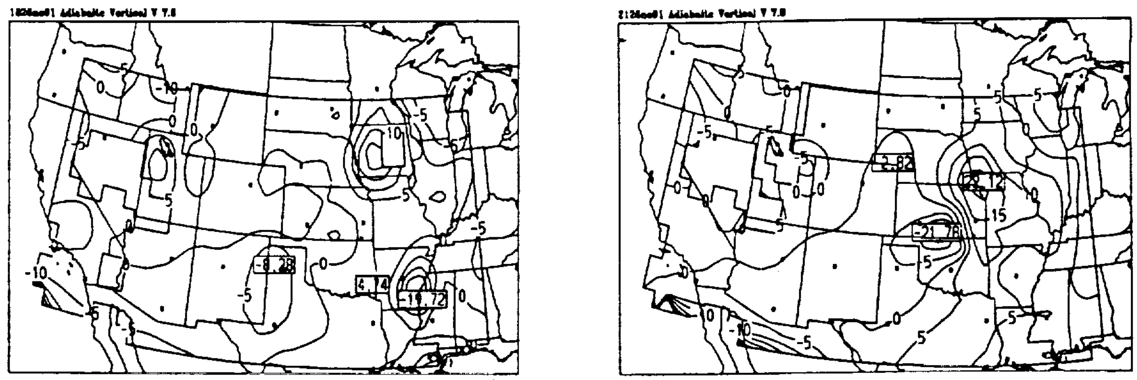

Fig. 4. Adiabatic vertical velocity for a) 18 UTC 26 Nov 91 and b) 21 UTC 26 Nov 91. Units are cm s^{-1}

ageostrophic as they passed through the difluent trough. The geostrophic adjustment process then contributed to upper level divergence and vertical motion.

Our future plans with this particular case study include investigating the source of the synoptic scale forcing in more detail. This includes examining the contributions of thermal advection and flow curvature on the vertical circulations that are evident from the present analysis. It is also necessary to show how the large scale water vapor budget contributed to the formation of the cloud system. Finally it is necessary to quantify the response of the macroscale cloud system to the dynamical forcing. This will be pursued using geostationary satellite imagery and cloud radar data.

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References

Davies-Jones, R. 1993: Useful formulas for computing divergence, vorticity, and their errors from three or more stations. *Mon. Wea. Rev.*, **121**, 713-725.

Hiroshi, A. 1978: A method of bivariate interpolation and smooth surface fitting for values given at irregularly distributed points. ACM-TOMS, Vol. 4, No. 2, June 1978.

Jensen, E. J., O. B. Toon, D. L. Westphal, 1993: Three dimensional modeling of cirrus during the 1991 FIRE IFO II: detailed process study. this issue

Keyser, D. and M. A. Shapiro, 1987: A review of the structure and dynamics of upper-level frontal zones. *Mon. Wea. Rev.*, **114**, 452-499.

Mitchell, D. L., S. K. Chai, Y. Dong, W. P. Arnott, J. Hallett, and A. J. Heymsfield, 1993: Importance of aggregation and small ice crystals in cirrus clouds, based on observations and an ice particle growth model. this issue

Sanders, F. 1988: Life history of mobile troughs in the upper westerlies. *Mon. Wea. Rev.*, **116**, 2629-2648

Shapiro, M. A., 1983: Mesoscale weather systems of the central United States. *The National STORM Program: Scientific and Technological Bases and Major Objectives*, R. A. Anthes, Ed., University Corporation for Atmospheric Research, P. O. Box 3000, Boulder, CO 80307, 3.1-3.77.

Thiebaux, H. J., and M. A. Pedder, 1987: *Spatial Objective Analysis*. Academic Press, 299 pp.

Whitaker, J. S., and A. Barcilon, 1992: Genesis of mobile troughs in the upper westerlies. *J. Atmos. Sci.*, **49**, 2097-2107.