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Examination of the Observed Synoptic Scale Cirrus Cloud Environment: The December 3-6 FIRE Cirrus Case Study

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1. Introduction

Recently, Sassen (1992) provided evidence for supercooled water droplets in cirrus uncinus cell heads at temperatures between -40^0 and -50^{0}C. Chemistry related to volcanic aerosol of stratospheric origin was evoked as an explanation fo this phenomenon. Sassen speculated that injections of sulfuric acid droplets into the upper troposphere were accomplished by tropopause folds associated with subtropical jet streams. He also postulated global climatic perturbations due to the effect of these cirrus microphysical perturbations on radiative fluxes.

Using data processing and objective analysis techniques described by Mace and Ackerman (1993, this issue), we examine the synoptic scale environment for evidence of tropopause folds that may have served as a source mechanism of stratospheric aerosol in the upper troposphere.

2. The Synoptic Scale Environment

Even though the cirrus cloud systems reported by Sassen (1992) occurred on 5 and 6 December, we chose to begin our examination of the broad-scale environment on 3 December 1991 during a highly perturbed period in the upper level air-flow. At 12 UTC 3 December 1991 (3/12), a sharp trough in the upper troposphere extended from a low near Hudson Bay through the central United States and into the Gulf of California. A southwesterly jet with speed maximum of 75 m/s extended from central New Mexico into the Canadian Maritime Provinces and northwesterly jet with speed

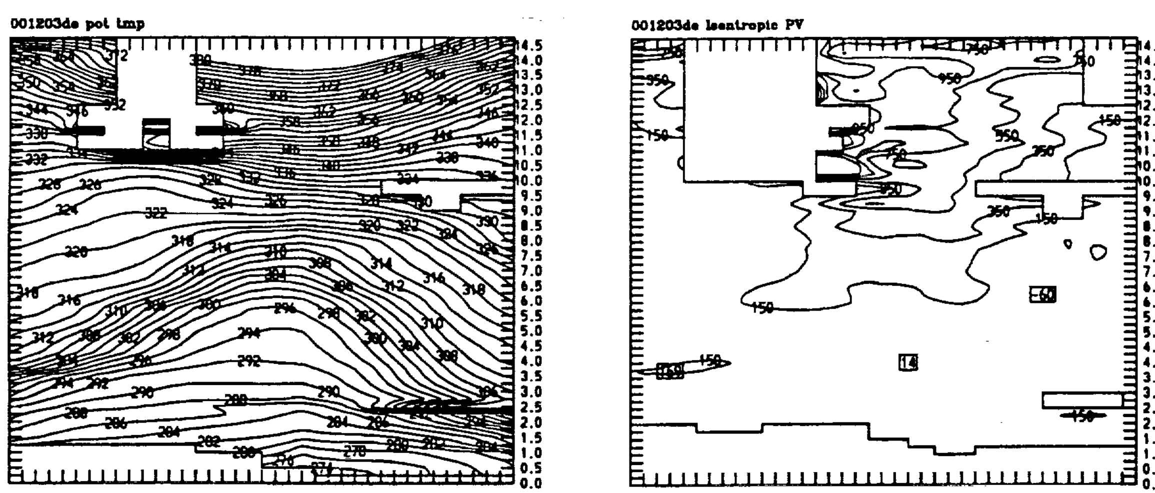

Fig. 1. Vertical cross sections of a) potential temperature and b) Isentropic Potential Vorticity normal to the airflow at 12 UTC 3 December 1991. The cross sections extend along a line from southwestern New Mexico to central Kansas and thence southeastward to central Louisiana. Blocked out portions of the figures denote regions of missing or erroneous data. Units of pontential are 10^{-7} K mb^{-1} s^{-1}.

maximum of 60 m/s extended from the Gulf of Alaska to the Desert Southwest of the United States.

Fig. 1 shows the vertical cross sections of potential temperature and potential vorticity along lines normal to the upper tropospheric flow. The vertical column where the cross section crosses the trough axis is evident by examining the potential temperature contours; the contours bend upward in the troposphere and downward in the stratosphere. To the left of the trough axis in the northwesterly flow, a well defined elevated frontal zone is evident. The frontal zone, roughly bracketed by the 304K and 310K isentropes extends from the tropopause near the trough axis downward to approximately 3 km in southwestern New Mexico. Associated directly with the upper front is a discontinuity in isentropic potential vorticity. This quantity can be considered a quasi-conservative tracer of air parcels in the upper troposphere. Fig. 1b shows that values of potential vorticity denoting air parcels of stratospheric origin (greater than 150 units) are diagnosed along the upper tropospheric frontal zone. This characteristic feature of upper tropospheric baroclinic zones has been shown to be indicative of extrusions of stratospheric air into the middle and upper troposphere; these extrusions are known as tropopause folds (Danielson, 1968; Shapiro, 1976). While no cirrus were directly associated with this event, tropopause folds have been documented as an injection mechanism of stratospheric aerosol of volcanic origin into the middle and upper troposphere (Shapiro, 1984). If enhanced aerosol loading existed in the lower stratosphere over the western third of North America, stratospheric aerosol were likely deposited into the middle and upper troposphere over a large portion of the western and southwestern United States by this fold event.

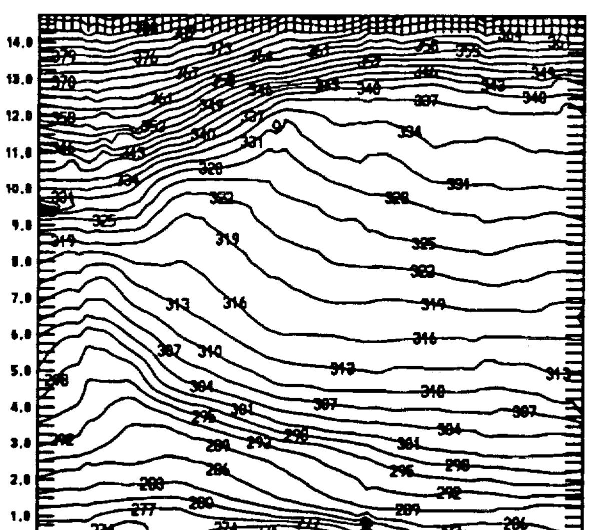

Fig. 2. Time-Height cross sections of potential temperature over Coffeyville, Kansas from 0000 UTC 3 Dec. 1991 to 1800 UTC 6 Dec. 1991.

The geographical extent of the elevated frontal surface becomes evident in light of Fig. 2. This time height cross section of potential temperature over Coffeyville show the elevated frontal surface in the northwesterly flow upstream of the trough axis after 3/12. This layer of enhanced static stability defined by the 292K and 304K isentropes was continuously observed at lower levels with the passage of time and could still be recognized as a distinct entity 36 hours later. Given a conservative mean advective speed of 20 m/s in the northwesterly flow, the longevity of this feature suggests an along-trajectory length scale of more than 2500 km.

A considerable deamplification of the upper level pattern took place on 4 Dec. The jet-trough system propagated northeastward in response to rising heights over much of western North America. This process is also evident in Fig. 2 as tropopause heights increased from 8 km late on 3 Dec. to near 12 km by 4/12.

By 5/00 the main belt of westerlies extended across southern Canada and the northern United States. A weak subtropical jet stream extended from the Four Corners region eastward along the Kansas-Oklahoma border. A band of cirrus existed at and below the level of maximum wind along the anticyclonic shear side of the jet streak. The position of the cirrus relative to the upper tropospheric flow is qualitatively in line with theoretical expectations of reduced static stability and upward motion below the level of maximum wind in the left rear quadrant of a jet streak (Maddox and Bleck, 1986). Vertical cross sectional analysis (not

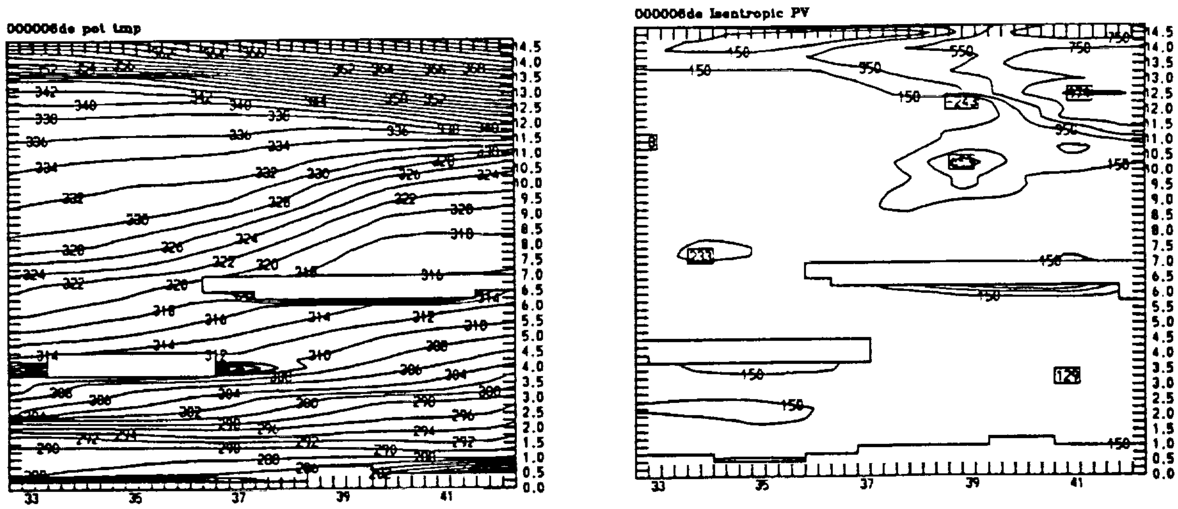

Fig. 3. Vertical cross sections of a) potential temperature and b) Isentropic Potential Vorticity normal to the airflow at 00 UTC 6 December 1991. The cross sections extend along a line from south-central Oklahoma to southern Nebraska..

shown) of this feature shows no near-tropopause baroclinic zones or obvious fold event associated with it.

The thermodynamic and wind structure of the next jet streak (centered at 5/20 and 11.5 km over Coffeyville) was better defined. The vertical cross sections normal to the upper tropospheric air flow at 6/00 (Fig. 3) reveal a weak elevated frontal zone bounded by the 320K and 330K isentropes that was well correlated with the region of largest cyclonic shear vorticity associated with the jet streak. Corresponding values of isentropic potential vorticity reveal a discontinuity from tropospheric to stratospheric values at the frontal interface strongly suggestive of a folded tropopause over central and northern Kansas. Satellite imagery shows that the cirrus observed during this period was part of an elongated shield of cirrus that extended eastward from central Colorado. The base of the cirrus clouds observed over Coffeyville (~ 37N) at this time were just above 9 km with tops near 11 km. The base height corresponds to the upper portion of the elevated frontal zone and the southern extent of the stratospheric potential vorticity in the cross section. Additionally, data from an ozone sonde launched at this time (Fig. 4) reveal a well defined spike in the ozone profile centered at 8.75 km. We conclude that the cirrus observed over Coffeyville at this time existed at and above the upper boundary of the elevated frontal surface and based on this analysis, the base of the cirrus clouds appear to have been in direct contact with air of very recent stratospheric origin.

The layer of enhanced static stability attributed to the upper front continues to be evident in the potential temperature cross sections at 6/12 and 6/18 (not shown) although the frontal zone appears to be disconnected from the tropopause and the IPV discontinuity is no longer evident. This six hour period roughly brackets the third cirrus event of this case study.

3. Summary, Conclusions and Future Work

We have provided evidence suggesting that the dynamic mechanisms necessary to explain a tropospheric source of volcanic aerosol did indeed exist during this case study period. An intense upper tropospheric polar jet-front system and associated tropopause fold affected much of western North America on 3 Dec. The following day (4 Dec) aerosol induced twilight affects were noted (Sassen, 1992) and the first cirrus cloud event of the case study (5/03-5/18) occurred. Although associated with a weak subtropical jet stream, this first cirrus event was not directly associated with any obvious

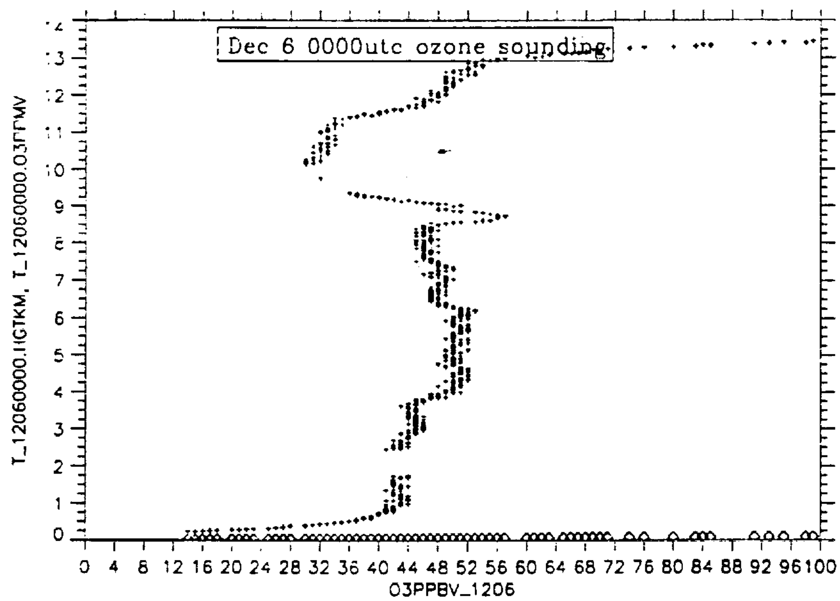

Fig. 4. Tropospheric ozone profile recorded by a sonde launched at the FIRE II hub site in Coffeyville, KS at 00 UTC 6 December 1991.

elevated frontal zone. The second cirrus cloud event took place from 5/18 to 6/06. The cirrus was also associated with a subtropical jet streak and the data revealed a weak elevated baroclinic zone in the upper troposphere with an associated region of high isentropic potential vorticity suggestive of a weak tropopause fold. Increased ozone in this layer provided supporting evidence.

Further analysis of these cirrus cloud events needs to concentrate on the moisture budget of the upper troposphere. While we have provided evidence to suggest that volcanic aerosol injection is a plausible in this situation, we have not addressed the troubling question of how the dehydrated stratospheric air parcels containing the sulfuric acid droplets gain enough moisture to form cirrus clouds.

Acknowledgments: This research was supported in part by NASA grants NAG-1-1095 and NAG-1-999 and by DOE grant DE-FG02-90ER61071. This work was done while one of us (GM) held a NASA Goddard Graduate Student Fellowship.

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