

PICTURE OF THE MONTH

Mesoscale Shear Eddies in the Upper Troposphere

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1. Introduction

Between 1200 and 1500 UTC on 17 April 1999, a series of mesoscale eddies formed east of the Rocky Mountains in Colorado and Nebraska. Although generally clear skies prevailed, the eddies were strikingly apparent in the *Geostationary Operational Environmental Satellite-8 (GOES-8)* water vapor imagery (Figs. 1–3). This case is unusual in that multiple eddies formed in a linear fashion and were well structured for a long temporal period. Initially there was a total of four eddies; only two of the eddies lasted 21 h. The eddies were approximately 150 km (93 mi) in horizontal scale for most of their lifetime; however, one eddy reached a maximum size of nearly 200 km (124 mi) over the border between Texas and Oklahoma at 0200 UTC 18 April 1999. After their formation, the eddies in eastern Colorado and Nebraska drifted southeastward into Kansas and Texas by 0000 UTC 18 April 1999 (Fig. 3). The eddies moved southeast then eastward into the panhandle of Texas before dissipating in extreme eastern Texas and western Louisiana at 1500 UTC on 18 April 1999. This article describes the atmospheric conditions at the time of the eddies and identifies factors that may have contributed to their formation.

2. Synoptic conditions

During the days of 17 and 18 April 1999 there was a highly amplified circulation pattern over North America. A large, positively tilted trough evident on the 400-mb map for 1200 UTC 17 April 1999 (Fig. 4) extended well into the middle sections of the United States. The trough was also detectable in the water vapor loop. Associated with this trough was a strong jet of 140 kt (72

m s^{-1}) on the east side in the southern United States. The west side of the trough was oriented nearly meridionally from New Mexico to North Dakota with winds generally less than 65 kt (34 m s^{-1}). A ridge at the upper levels dominated the western United States.

Embedded within the synoptic field, a short-wave trough, defined by a wind shift line, sliced through the central Dakotas. The wind shift line is best defined at the 250-mb level (not shown); however, the short-wave trough is present at the 400-mb level without the distinct wind shift. Winds at the 400-mb level decreased in magnitude toward the south along the wind shift line, creating confluence in the region where the eddies formed. The short-wave trough further intensified by 0000 UTC 18 April 1999, when cyclonic rotation was evident in the water vapor loop.¹ The eddies formed in the region of strongest horizontal wind shear, which occurred on the west side of the short-wave trough. As will be discussed later, the short-wave trough may have been a key ingredient in the formation of these eddies.

After forming, the eddies primarily followed the northerly wind flow between 850 and 250 mb. Soundings were obtained to show the vertical profile of the wind field at several locations during the formation of the eddies. A sounding from Denver, Colorado (DEN), at 1200 UTC 17 April 1999, shown in Fig. 5, was able to record the vertical profile in the area close to where the eddies originated. This area of formation is apparent in the water vapor image as the darker filament extending from central South Dakota southwest into Colorado (Fig. 1). One striking feature of the sounding is that there is weak vertical wind shear present above the planetary boundary layer. There is also a very distinct inversion between 650 and 600 mb where the dewpoint decreases sharply. This is characteristic of the vertical profile in the vicinity where the eddies were present. A

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¹ A loop of the water vapor images is available at the author's Web site: <http://uiatma.atmos.uiuc.edu/~weinand/eddies.html>.

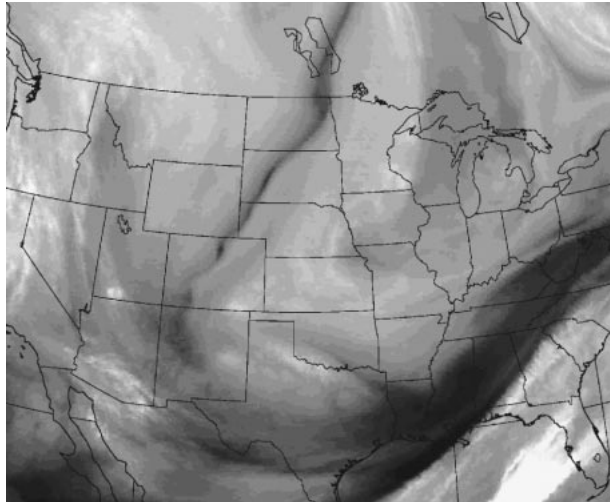


FIG. 1. GOES-8 water vapor image for 1200 UTC 17 Apr 1999 showing formation of mesoscale shear eddies over north-central Colorado.

northerly jet was located west of the shear zone where the eddies formed, implying strong vertical speed shear. The sounding from Grand Junction, Colorado (not shown here), confirmed this observation. Weak vertical shear and strong horizontal shear can thus characterize the wind fields.

3. Possible forming mechanisms

a. Horizontal wind shear and jet streaks

The eddies initially developed in a zone of strong horizontal cyclonic wind shear located in a zone from north-central South Dakota to central Colorado (Fig. 1). The shear zone is an artifact of a short-wave trough identified in the previous section. Jet streaks embedded

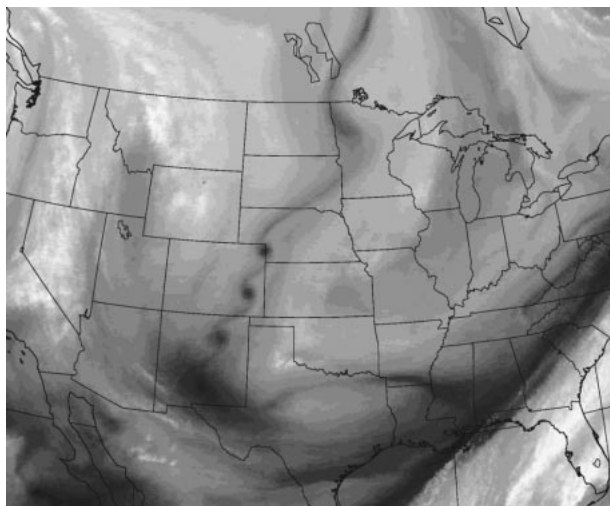


FIG. 2. Fully developed mesoscale eddies over eastern Colorado and northern New Mexico at 1800 UTC 17 Apr 1999.

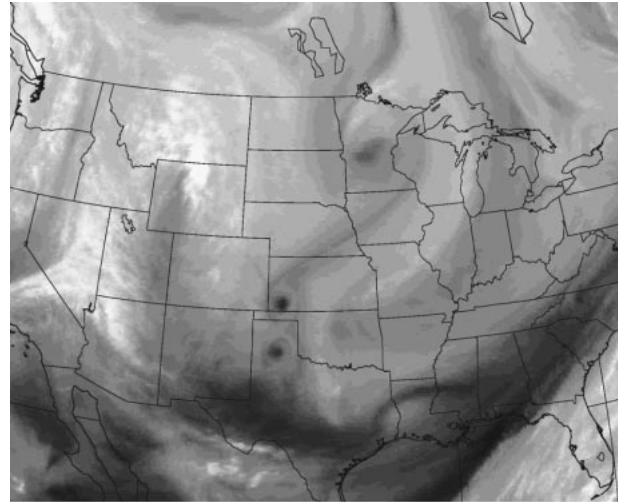


FIG. 3. As in Fig. 1 but for 0000 UTC 18 Apr 1999.

in the 400-mb flow aided in the increased horizontal wind shear located where the eddies formed (Fig. 4). This can be shown by matching the eddies position with the 400-mb jet streaks, area of maximum horizontal wind shear, over the lifetime of the eddies.

At 1200 UTC 17 April 1999, the area of strong wind shear extended from South Dakota through west-central Nebraska (Fig. 1). At this time the water vapor loop shows that the shear zone has been perturbed, and waves can be seen in the shear zone in north-central Colorado and extending into western Nebraska. Concurrently, a small jet maximum of 60 kt (31 m s^{-1}) was located parallel to and just northeast of the waves seen in the water vapor image (Fig. 4). The jet maximum then continued to move south, and the Eta Model 6-h forecast valid at 1800 UTC 17 April 1999 shows it was located from northeast Colorado southward into north-central

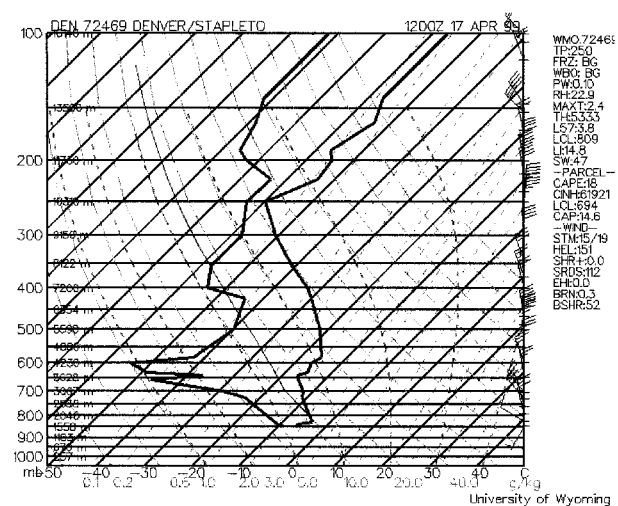


FIG. 4. Sounding for Denver, CO (DEN), at 1200 UTC 17 Apr 1999 showing vertical wind structure in area of eddy formation.

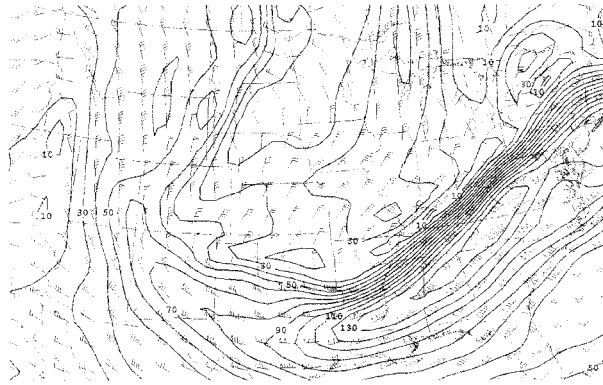


FIG. 5. Eta analysis of 400-mb winds (kt) and isotachs (kt) for 1200 UTC 17 Apr 1999. The 60-kt jet streak is located over the border of eastern Wyoming and western South Dakota.

New Mexico. This is located parallel to and slightly west of the eddies at 1800 UTC, and also west of the area of strong horizontal wind shear. Subsequently, the eddies continued to organize further and became more apparent in the water vapor pictures. By 1800 UTC three eddies were well defined over Nebraska and extending southwest into Kansas and New Mexico (Fig. 2). Eventually, the jet maximum merged with the tail of the zonal jet located in the southern United States. The eddies persisted until 1200 UTC on 18 April 1999 when they weakened and disappeared in the strong zonal jet over east Texas.

Simple calculations of horizontal wind shear on the cyclonic side of the jet streak at 400 mb produced values of 12 kt per 100 km (6.2 m s^{-1} per 100 km). After matching up the position of the eddies with the wind shear calculations, the eddies occurred directly in the zone of strongest local horizontal wind shear. Once the eddies moved slightly out of this zone, that is, the southernmost eddies, they became more diffuse and eventually decayed. Thus an argument can be made that the eddies were primarily formed due to the horizontal wind shear associated with the synoptic pattern.

Besides creating horizontal wind shear, the 400-mb jet streak stretched filaments associated with the eddies. As the jet streak moved south it produced perturbations that later became better-organized eddies. Calculations of stretching deformation in Fig. 6 show positive values of $1.0 \times 10^{-4} \text{ s}^{-1}$ along the cyclonic side of the jet streak. The positive values of stretching deformation are associated with the region where the eddies formed. Stretching deformation values were $1.5 \times 10^{-4} \text{ s}^{-1}$ 12 h before the eddies formed, and decreased to $4.0 \times 10^{-5} \text{ s}^{-1}$ 24 h later. This shows that stretching deformation was nearly strongest when the eddies formed. These results imply that the 400-mb jet streaks provided the influx of momentum, and the synoptic flow concentrated this momentum, tightening the horizontal wind gradient. The result was a region of strong horizontal wind shear in which the eddies were maintained. In support of this

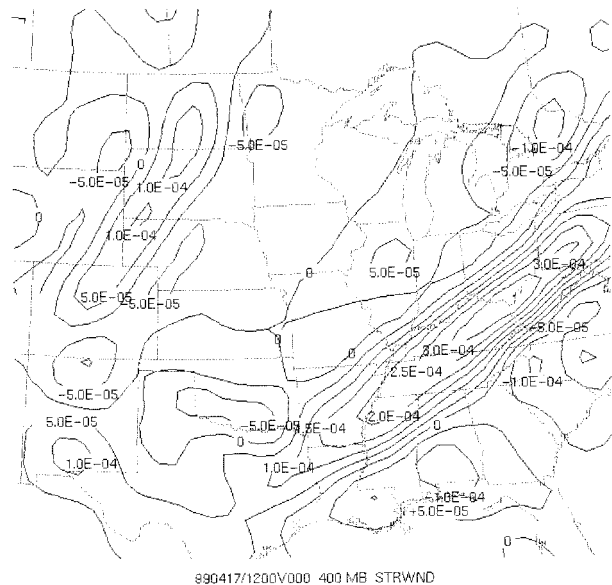


FIG. 6. Stretching deformation (s^{-1}) at 400 mb from Eta horizontal winds valid for 1200 UTC 17 Apr 1999. Values are positive and locally higher in region where eddies formed.

hypothesis, the water vapor image show the eddies appear after 1200 UTC, which is when stronger stretching occurred. This stretching might be the atypical occurrence that led to the formation of such unusual eddies.

b. Barotropic instability

While horizontal wind shear and the jet streak at 400 mb may have been responsible, barotropic instability could also have led to the formation of the eddies. One criterion for barotropic instability is that the meridional gradient of absolute vorticity must be zero somewhere in the vicinity where the eddies develop (Holton 1972, pp. 290–294). A simple calculation proposed by Nitta and Yanai (1969) was used here to test the criterion. Using the absolute vorticity analyses from the Eta Model at 1200 UTC and the Eta Model 6-h forecast valid for 1800 UTC 17 April 1999, the absolute vorticity was calculated as a function of latitude at different vertical levels. Areas where the absolute vorticity are a maximum satisfy the instability criterion. At 1200 UTC 17 April 1999 the criterion was best satisfied above 400 mb where the eddies formed in western Nebraska and northeast Colorado. The criterion was also met at 1800 UTC 17 April 1999 where the eddies were present over eastern Colorado and northeast New Mexico.

In addition to the above criterion, barotropic instability requires the absence of vertical wind shear. The soundings for Dodge City, Kansas (DDC), and Amarillo, Texas (AMA), at 0000 UTC 18 April 1999 exemplify there was very little vertical wind shear present. Figure 7a shows the vertical wind structure in the region of Dodge City. This sounding was taken when one of

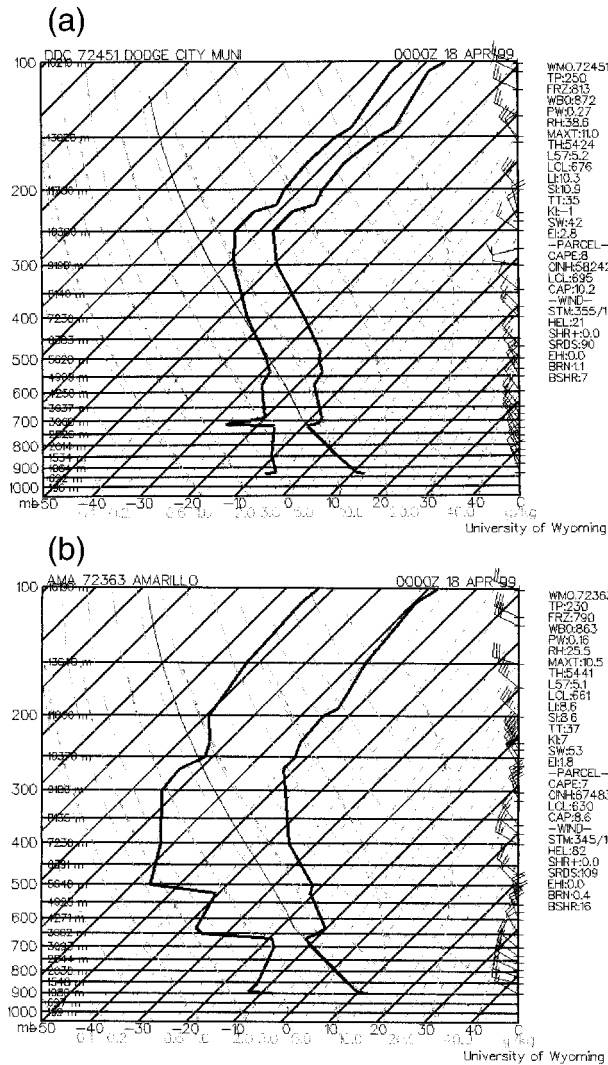


FIG. 7. (a) Sounding for Dodge City, KS (DDC), for 0000 UTC 18 Apr 1999 showing possible vertical wind field through eye of a mesoscale eddy. (b) Amarillo, TX (AMA), sounding for 0000 UTC 18 Apr 1999 showing vertical wind structure in region of eddies.

the eddies was almost directly overhead. The wind is from the northwest at 10–30 kt ($5\text{--}16\text{ m s}^{-1}$) from the surface up to 300 mb. In the 200–300-mb layer the winds are weaker than the winds above and below as well as variable in direction. This is the region where the eddies were likely present. The very weak winds between 300 and 200 mb may indicate that the radiosonde passes near the center of the eddy. The Amarillo sounding is also noteworthy since its location is near the southernmost eddy at 0000 UTC 18 April 1999 (Fig. 2). The winds in this example are not as uniform as Dodge City, but it clearly shows that the wind field contained little vertical variation in the zone of the eddies. The Amarillo sounding might have clipped the northeast side of one eddy. In Fig. 7b, there is a northwest 55-kt (28 m s^{-1}) wind maximum just below 250

mb. The sounding may have drifted with the northwesterly wind flow and captured the tangential velocity associated with these eddies.

c. Orography

The role of topography may also have been important in the formation of the eddies since an axis of absolute vorticity associated with the short-wave trough did not start to ripple and form eddies until it reached the eastern Rocky Mountain region. While the arguments given by horizontal wind shear, jet streaks, and barotropic instability might well be sufficient to explain the eddies, the southern edge of the shear zone did pass over the eastern peaks of the Rocky Mountains in southeast Wyoming and eastern Colorado. The southern edge of the wind shear zone at this point was perturbed slightly. The first two eddies formed 1 h before the northern eddies that did not flow over topography. There is much literature on flow over obstacles that might help explain the eddies in this case. Among the many earlier papers investigating airflow over obstacle, the work of Hubert and Krueger (1962) is noteworthy because it illustrates eddies of nearly the same size as those shown here. The earlier eddies occurred in the Atlantic Ocean and were created by the mountain island Madeira of the Canary Islands group. The explanation of these eddies involves more than topography since the flow was over the ocean and not entirely perpendicular to the mountains in a zonal direction. It does prove that eddies can be formed due to topography. It is not clear, however, how interaction between the upper-level short-wave trough axis and the eastern peaks of the Rocky Mountains can explain the long-lasting eddies in the present case.

4. Summary

Even with hypotheses such as those given above, it is not apparent why small eddies formed in such an extraordinary fashion. The horizontal shear that produced the eddies was not extreme: at the concurrent time there was even stronger wind shear associated with a 130-kt (67 m s^{-1}) jet stream on the east coast of the United States. Horizontal wind shear values on the cyclonic side of this jet exceeded 68 kt per 100 km (34.9 m s^{-1} per 100 km). Additionally, winds often come from the north or northwest over the Rockies in a pattern similar to that of this case, but it is unusual to observe the type of eddies shown here. The strong confluence over the Kansas–Nebraska–Colorado region appears to be atypical, and its possible role in the eddy formation merits further investigation.

Another consideration is that other occurrences of such eddies are generally accompanied by clouds and precipitation, which would contaminate the depiction of eddies in a water vapor image. Such examples would include mesovortices associated with decaying mesoscale convective complexes. Since these mesovortices

have very dense cloud cover associated with them, large amounts of water vapor are ejected into the upper regions of the atmosphere and sometimes do not allow the viewer to see the true structure of the underlying mesovortex.

Finally, there is the possibility that the instability leading to the eddies here might be larger than in other examples of mesoscale eddies. Water vapor images show a dry patch at the center of the eddies indicating good structure (Fig. 2). Other cases, however, are not available for comparative evaluation.

5. Conclusions

It appears that this example of shear eddies is atypical, as many weather enthusiasts who were shown this case were unable to recall other examples. It is apparent that the horizontal wind shear produced by the short-wave trough and the stretching deformation produced by the 400-mb jet streak are promising hypotheses for the explanation of the formation of the eddies. The enhancement of the southern eddies by orography and the maintenance of the eddies by barotropic instability may help explain why the eddies lasted so long. Whatever the physical basis of the eddies, this example illustrates the advantage of high-resolution water vapor imagery in the

detection of mesoscale features that would have otherwise gone unnoticed.

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