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Title: NOCTURNAL WIND DIRECTION SHEAR AND ITS POTENTIAL IMPACT ON POLLUTANT TRANSPORT

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Nocturnal Wind Direction Shear and its Potential Impact on Pollutant Transport

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1. INTRODUCTION

The estimation of transport and diffusion of airborne pollutants during the nighttime is challenging, especially over complex terrain where gravity driven drainage flows may be overlain with wind from a different direction. For example, during the Atmospheric Studies in Complex Terrain (ASCOT) program's wintertime field project at Rocky Flats, Banta et al. (1995) used lidar data to illustrate a case in which a 2-km-wide canyon drainage jet overlay a persistent surface drainage wind. This jet was the likely explanation for an observed secondary plume in the tracer data. Banta et al. (1993), is discussing the same site, point out that "... because of the strong vertical layering and horizontal variability, contaminants released at different heights or at slightly different locations in the horizontal could easily be advected along widely divergent trajectories." Working with data from the same area, Porch (1996) demonstrates that a surprisingly shallow canyon (10 to 20 m deep) can have a significant effect on transport. These studies and others suggest that knowledge of the vertical wind structure, in addition to its horizontal structure, can be very important in describing the trajectory of a plume under stable conditions, when the coupling between the near-surface flow and the flow above is weak and significant vertical wind shear can develop.

This study investigates the character of wind direction shear in the lowest 100 m using tower measurements from a complex, semi-arid site where local thermally-driven flows are common. The effects of wind direction shear on plume transport are studied by simulating a hypothetical elevated term release. This is accomplished by first simulating transport and dispersion using wind measurements from only the 12-m level from a network of towers. This case represents the approach commonly taken at many facilities where a network of short towers is available. Then the release is modeled using wind measurements made at four levels in the lowest 100 m. The differences between the two simulations are significant and would lead to very different responses in an emergency situation.

2. SITE DESCRIPTION AND MEASUREMENTS

The site is the Los Alamos National Laboratory (LANL). It is located 100 km north-northeast of Albuquerque and 40 km northwest of Santa Fe in north-central New Mexico. The Laboratory is situated on the Pajarito Plateau on the eastern flanks of the Jemez

Mountains. This plateau slopes about 2.5° to the east-southeast, covering a distance of more than 24 km from the base of the Jemez Mountains to the edge of White Canyon, which is part of the much broader Rio Grande River Valley. The Jemez Mountains to the west of the site rise 900 m above the plateau, and cooled air sliding off this elevated terrain contribute the frequently observed drainage flows on the plateau. The Rio Grande Valley to the east of the site runs from north-northeast to south-southwest and appears to have a large effect on wind direction above the shallow drainage flows over the plateau.

The Air Quality Control Group at LANL operates a network of meteorological stations to support emergency response, regulatory modeling, and a variety of other applications (see Stone and Holt [1996] for details). This study uses wind direction and wind speed measured at four tower stations located on the plateau (Fig. 1). The TA-49, TA-53, and TA-54 towers are instrumented 12, 23, and 46 m above ground level (AGL), and the TA-6 tower is instrumented at 12, 23, 46, and 92 m AGL. Measurements of temperature and the standard deviation of wind direction (σ_θ) made at the TA-6 tower are also used to estimate dispersion parameters. All measurements are sampled at a 0.33 Hz and the data archived as 15-min averages.

Annual surface wind roses for nighttime (Fig. 1) demonstrate the strong influence that the local terrain has on the wind near the ground. The preponderance of fair skies, light gradient winds, and low humidity promote formation of a low-level drainage wind, especially close to the mountains on the western edge of the site (i.e., at TA-6 and TA-49). Drainage winds are also frequent at the TA-54 station, but they are shallower than those observed closer to the mountains. Infrequent drainage flow at the TA-53 station is explained by its location on a narrow mesa separating two large canyons.

3. RESULTS

3.1 Wind Shear Statistics

Probability distributions for wind shear between 12 m and 92 m AGL at the TA-6 tower are shown in Fig. 2. The data sets consisted of 15-min average values of wind direction for daytime (09 to 17 MST) and nighttime (20 to 05 MST) over a one year period. These distributions show a slightly greater probability for negative shear values, i.e., the wind backs with height more often that it veers with height. Negative shear values often represent periods when southerly upper-level flow overlies westerly drainage fow at the surface; and positive values often represent periods when northerly flow overlies the surface drainage flow.

As expected, the distribution for nighttime shear is much broader than that for daytime; the standard deviation of shear for daytime and nighttime are 19° and 49°, respectively. Both distributions are non-Gaussian, having large values of kutosis (resulting from long, rather flat tails in the probability density distributions). The 90th percentile of the absolute value of shear is approximately 20° during the day and 80° for nighttime. Analysis of shear at the other towers produced similar results, which supports the notion that large values of wind direction shear occur frequently during the night at this site.

3.2 Plume Simulations

The Atmospheric Release Advisory Capability (ARAC) modeling system was used to investigate the effects of vertical wind direction shear on the surface concentration pattern from an elevated release. ARAC is a centralized plume modeling system capable of providing real-time consequence assessment of hazardous atmospheric releases anywhere in the world (Sullivan et al., 1993). Wind fields were based on a $1/r^2$ interpolation scheme that used 15-min averaged winds from the four towers. Dispersion was modeled using ADPIC, which is a random displacement method of determining three-dimensional diffusion (Ermak et al., 1995). Important parameters used in the simulations are summarized in Table 1.

Table 1. Parameters used in the wind field and plume simulations.

horizontal grid vertical grid	50x50 cells, $\Delta x = 400$ m 30 cells, $\Delta z = 11.5$ m
release duration	one hour
release height	50 m AGL, no plume rise, deposition velocity = 0
z_0	0.5 m, estimated from turbulence studies
boundary layer depth	200 m, assumed
stability	F, estimated using Pasquill's turbulence types ????
Monin-Obukhov length scale	17 m, estimated from z_0 and stability
horizontal diffusivity, K_x and K_y, for the 12-m wind case	determined from measured σ_θ at 12 m AGL and extrapolated upwards
horizontal diffusivity, K_x and K_y, for the 12-to-92-m wind case	determined from measured σ_θ at all tower levels
vertical diffusivity, K_z	based on similarity theory using the estimated L

To study the effects of shear on plume transport, material was released into a highly sheared wind field from an elevated source point about 1.5 km northwest of the TA-6 tower. Figure 3 shows that the magnitude of the shear between the surface and the release height was about 45° during the release and for an hour afterwards. The flow at 12-m AGL was westerly at 2 to 3 m/s; and at 46 m AGL, just below the release height, the flow was southwesterly at less than 2 m/s. Measurements from the 92-m level show that the wind continued to back with height above the release point, becoming south-southwesterly at 92 m AGL. The 12-to-92-m shear had a value of about 75° for the entire period of the simulation. Meteorological conditions for early morning of October 10, 1994, were chosen for the simulations because they exhibited large vertical shear and were relatively steady in time.

Interpolated wind fields for 0400 MST are shown in Fig. 4a-b. Near the surface (Fig. 4a), westerly to northwesterly winds of about 2 ms $^{-1}$ are common over the entire plateau, indicating the presence of drainage winds; and, as indicated in Fig. 3, this drainage flow was very steady from 0300 to 0630 MST. The first of the two plume simulations (discussed below) used as series of wind fields computed from only the 12-m wind observations at each of the four towers. In each wind field, one for each 15-min time step, wind speed was extrapolated upwards using the standard power law, but wind direction did not change with height at a given location.

The wind field at 46 m AGL (Fig. 4b) was very different from that at the surface. In the northern half of the domain the flow converges in a zone over Los Alamos town. During the 3.5 hours over which the plume was tracked in this study, this convergent zone drifted a couple of kilometers to the east, but it remained a persistent feature of the wind field at this level. Flow between the release point and the convergent zone was steadily from the southwest and flow on the eastern side of the convergent zone was steadily from the north-northeast. In the southern half of the domain, the convergent zone was weaker and much more variable in time; sometimes the TA-49 wind had an easterly component, sometimes a westerly component. The second plume simulation (discussed below) used a series of fields based on all available wind measurements (the 12- , 23-, and 46-m levels at all four towers and the 92-m level at the TA-6 tower). In this case, observed changes in both wind speed and direction were incorporated into the interpolation, achieving a more realistic three-dimensional wind field history for the dispersion simulation.

The ADPIC dispersion results obtained from these two sets of wind fields are shown in Fig 5a-b. Figure 5a shows the location of the plume at 0500 MST, two hours after the start of the one-hour release. Here the concentration at 1.5 m AGL has been normalized by the source strength. The northwesterly drainage flow transports the plume to the community of White Rock. This case, referred to as the "12-m wind case," illustrates the result that would be obtained from a strategy commonly used at facilities where a network of short towers is available.

The other simulation, referred to as the "12-to-92-m wind case," used wind fields based on all the wind measurements made in the 12-to-92-m layer. Figure 5b shows the location of the plume for this case at 0500 MST. As the wind field of Fig. 4b suggests, the plume travels to the northeast and gets caught in the convergent zone over Los Alamos.

As time goes on, the surface-based drainage wind transports all the material over the community of White Rock in the 12-m wind case. The affected area is a narrow corridor southeast of the release point. In the 12-to-92-m wind case the plume is stretched and distorted in the elevated convergence zone over Los Alamos, and by the time it mixes down to the surface it affects a relatively large, oblong area oriented roughly north-south. When the time-integrated surface concentration patterns for the two cases are superimposed on a common map (Fig. 6) it is clear that including the effects of wind shear in the calculation can lead to very different—and presumably more realistic— results.

4.0 Discussion and Conclusions

At a complex, semi-arid site in north-central New Mexico, a large plateau slopes gently toward a large valley. Gravity driven flows along the surface of the plateau interact in a complex way with upper-level flow that is often has a large along-valley component. This interaction often leads to large directional shear in the lowest 100 m during the night; the root mean square value of the shear is about 50° at this site.

The potential impact of vertical wind direction shear on plume transport was illustrated with two simulations of an elevated release. In the first simulation, the 12-m wind case, only the near-surface wind measurements were used, and the elevated plume followed the streamlines of the steady drainage flow and impacted the downstream community. In the second, the 12-to-92-m case, wind measurements from four levels up to 92 m AGL were used. In this case the plume encountered an upper-level convergence zone and spread over a different community about 10 km from the first. Ignoring the vertical shear effects in this hypothetical situation would have resulted in serious mistakes in responding to the emergency. Although the conditions chosen for this comparison were rather extreme, they may occur often enough at some sites to be of concern for emergency managers.

It has been shown that a relatively dense network of near-surface wind measurements is often inadequate for modeling the consequences of elevated releases at complex sites during the nighttime. At facilities where credible accidents may lead to elevated releases, it is important to design the measurement network to capture the shear effects at the scale of interest. It is also important to use a modeling system that is capable of using vertical wind profiles and that the treatment of diffusion is suitably matched to the wind model. Reliance on near-surface wind patterns could lead to serious mistakes when responding to an emergency. At facilities where elevated releases are not credible accidents, or where operations are restricted to daytime, the shear effects on plume transport is of less concern.

In the analysis it is assumed that the simulation using all the tower measurements is more realistic. Although this is almost certainly the case, the more realistic result may still be inaccurate because of scales of motion not resolved by the tower network. Evidence for this comes from a study of the adequacy of the Los Alamos network by Lee et al. (1994).

When wind directions predicted by a 1/r^2 model were compared to field measurements made a few kilomters from a network tower station, the root mean square error in the predictions was about 40°, so interpolated wind fields like the ones used in this study are highly smoothed representations of the real flow. Also, because the horizontal transport of material in a highly sheared flow depends on where the material is in the vertical, the parameterization of vertical diffusion also plays an important role in the process.

As a final note of caution, it must be recognized that in the emergency response application the problem is to *predict* the plume trajectory, and this compounds the problem enormously. The conditions used in these simulations were carefully chosen to minimize the time variation in the problem, but in reality the wind field at a given level may change significantly during the incident.

Figure Captions:

Fig. 1. Map of the Los Alamos area showing the four tower stations on the Pajarito Plateau. The wind roses are for nighttime winds measured at 12 m AGL using one year of data.

Fig. 2. Cumulative probability distributions for wind direction shear between 12 m and 92 m AGL at TA-6. The data set consists of 15-min average values of wind direction for daytime and nighttime for a one-year period.

Fig. 3. Time series for wind direction and speed at 12 m and 46 m AGL near the elevated release point. The shaded band indicates the time of the hypothetical release on October 10, 1994.

Fig. 4. Diagnostic wind field at 12 m AGL (a) and 46 m AGL (b) at 0400 MST, at the end of the release.

Fig. 5. Normalized concentration pattern at 1.5 m AGL for the 12-m wind case (a) and the 12-to-92-m wind case (b) at 0500 MST. The cross (+) marks the location of elevated release point.

Fig. 6. Time-integrated, normalized concentration patterns for the 12-m wind case and the 12-to-92-m wind case. The integration time is 0300 to 0630 MST.

5. ACKNOWLEDGMENTS

??? ... This work was performed under auspices of the Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

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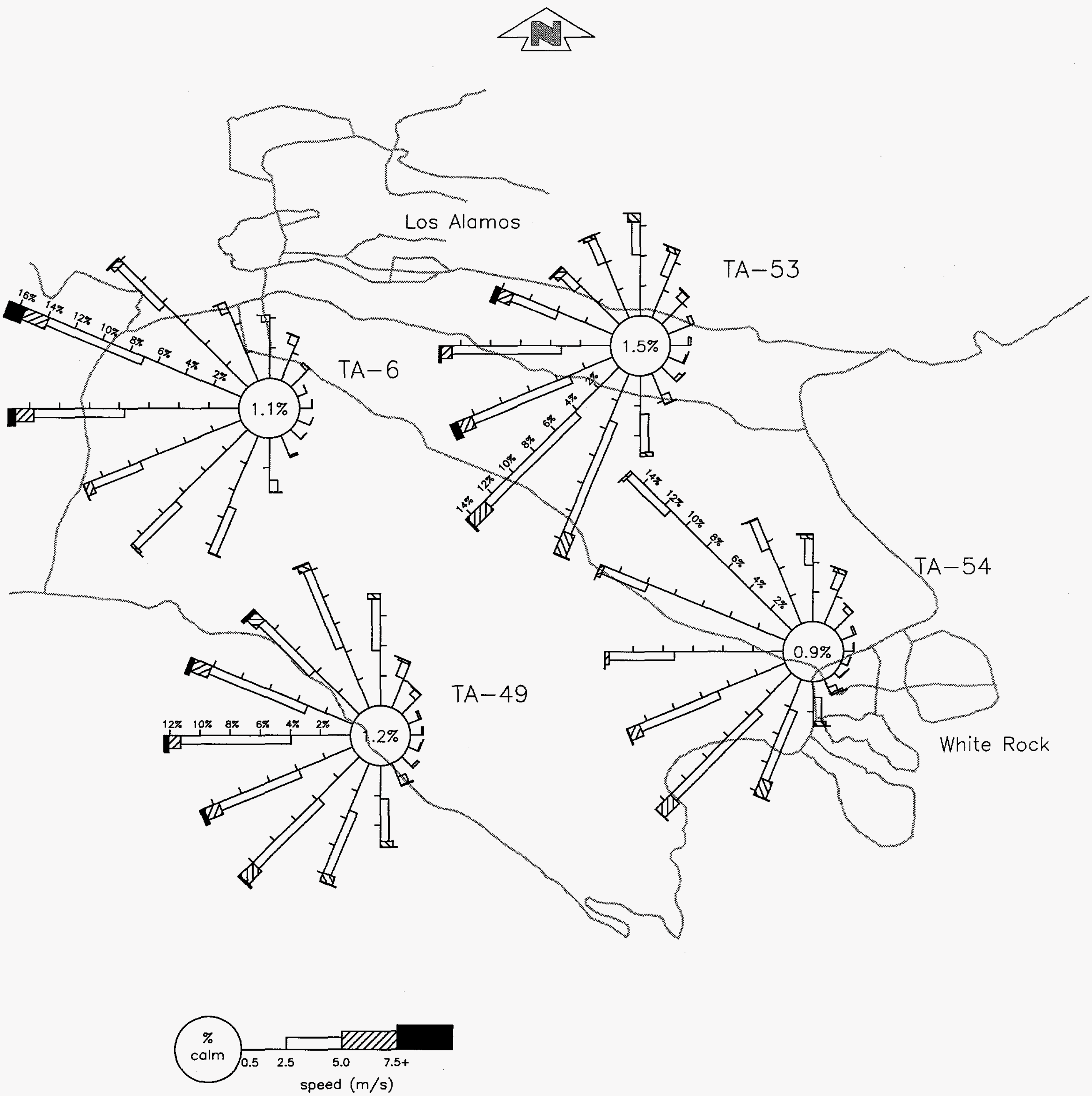


N
Los Alamos
TA-53
1.5%
TA-6
1.1%
TA-54
0.9%
TA-49
1.2%
White Rock
16%
14%
12%
10%
8%
6%
4%
2%
%
calm
0.5
2.5
5.0
7.5+
speed (m/s)

Fig. 1

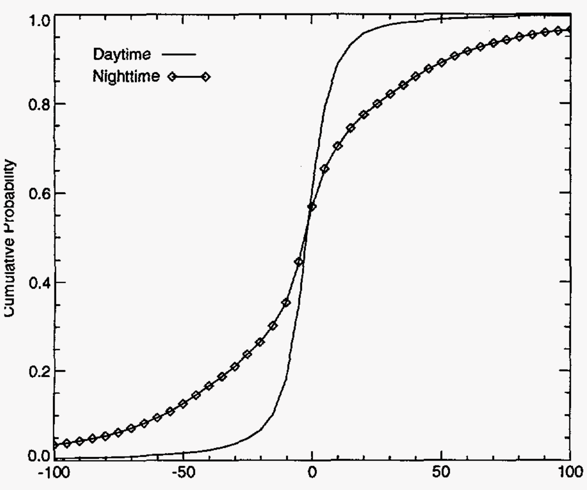
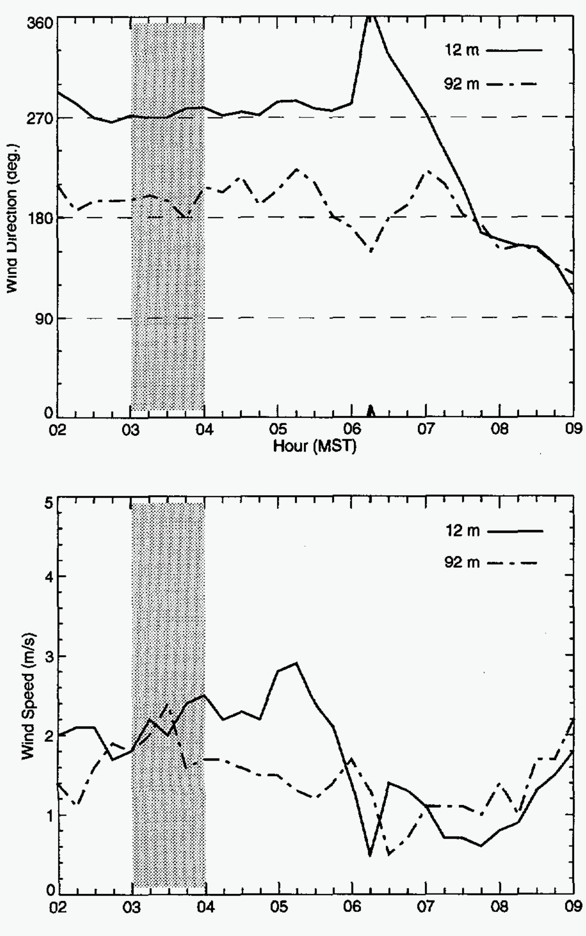
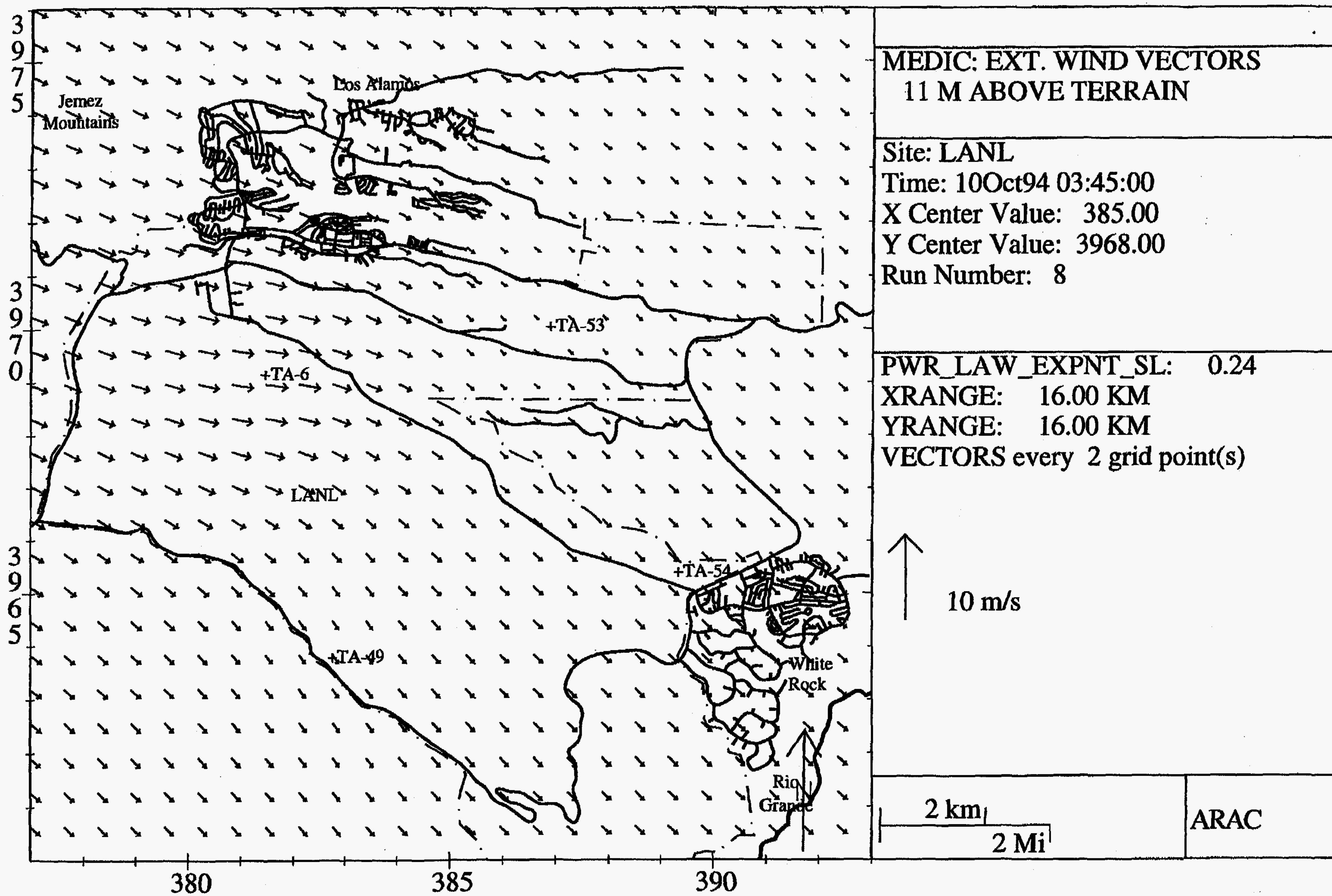

Daytime
Nighttime
Cumulative Probability
1.0
0.8
0.6
0.4
0.2
0.0
-100
-50
0
50
100

Fig. 2



12 m
92 m
Wind Direction (deg.)
360
270
180
90
0
02
03
04
05
06
07
08
09
Hour (MST)
Wind Speed (m/s)
5
4
3
2
1
0

Fig. 3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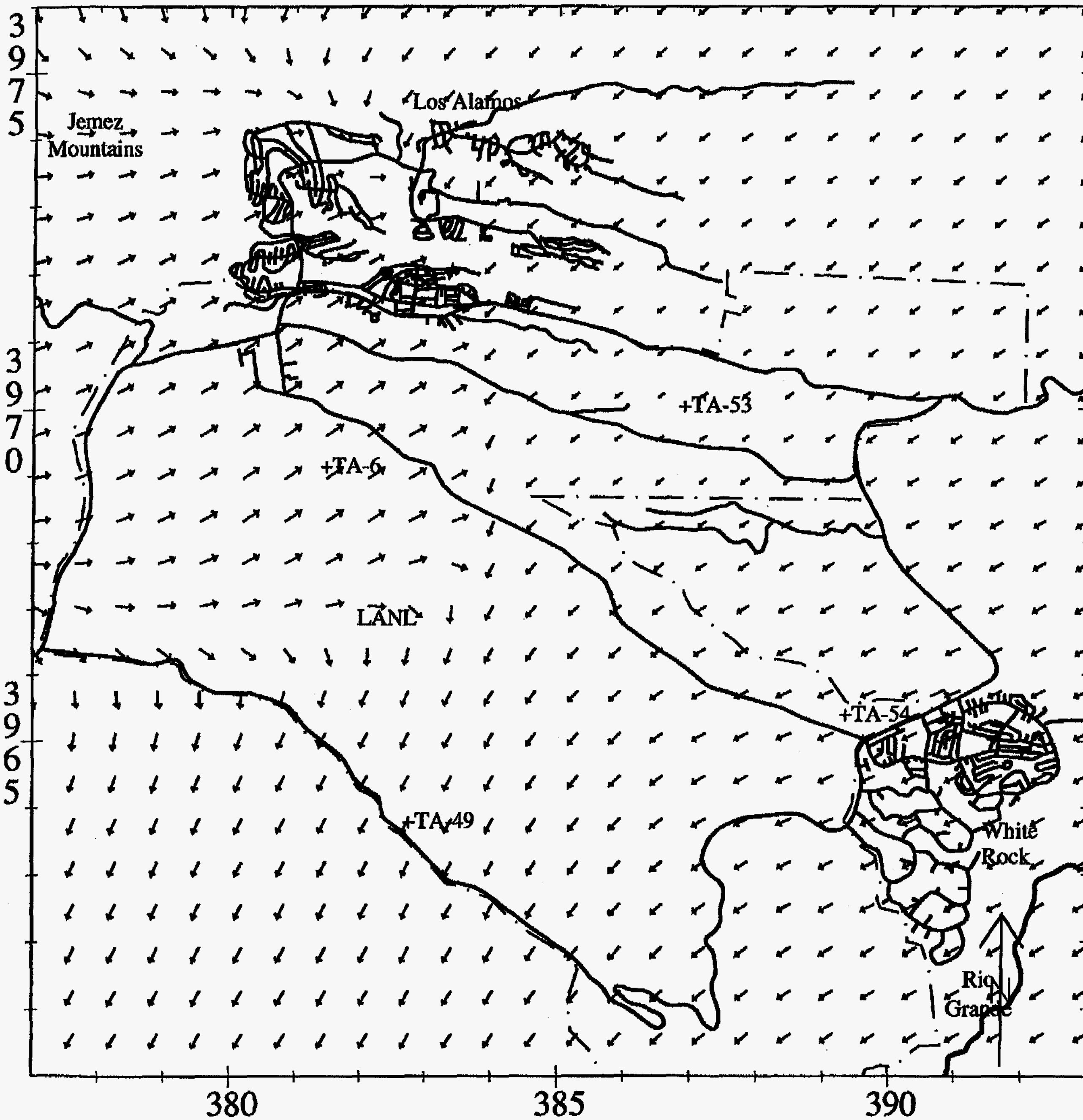
11 M ABOVE TERRAIN
Site: LANL
Time: 10Oct94 03:45:00
X Center Value: 385.00
Y Center Value: 3968.00
Run Number: 8
PWR_LAW_EXPNT_SL: 0.24
XRANGE: 16.00 KM
YRANGE: 16.00 KM
VECTORS every 2 grid point(s)
10 m/s
2 km
2 Mi
ARAC
Jemez Mountains
Los Alamos
+TA-53
+TA-6
LANL
+TA-54
+TA-49
White Rock
Rio Grande
3975
3970
3965
380
385
390

Figure 4a.



MEDIC: EXT. WIND VECTORS
46 M ABOVE TERRAIN

Site: LANL
Time: 10Oct94 03:45:00
X Center Value: 385.00
Y Center Value: 3968.00
Run Number: 8

PWR_LAW_EXPNT_SL: 0.24
XRANGE: 16.00 KM
YRANGE: 16.00 KM
VECTORS every 2 grid point(s)

10 m/s

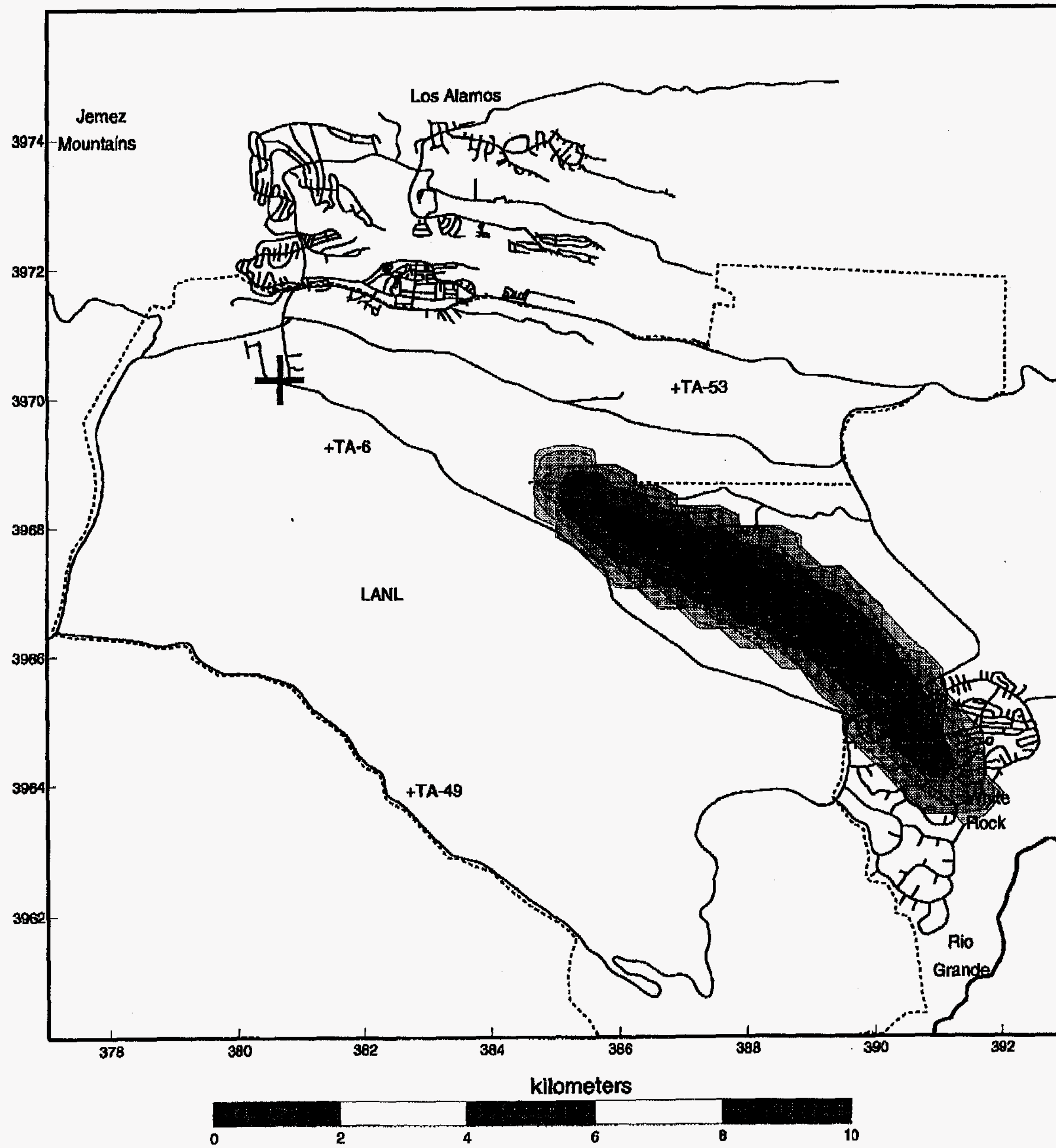
2 km
2 Mi

ARAC

Figure 4b.

50-m rel., 12-m winds, meas. sig. thet

LANL 10 OCT 1994 vertical shear study



Plot Generation Time
19AUG97 22:38:00 UTC

Contour Type
Instantaneous air at 1.5 meters
10OCT94 05:00:00 UTC

Material
Hypothetical

Source Location (longitude, latitude)
106° 19' 19" W, 35° 52' 11" N

Source Location (x, y, projection)
380.67 km E, 3970.30 km N, UTM

Remarks
One hour unit release: 0300-0400 MST
1-m sphere, 50-m high, no exit vel.
No deposition; Zo= 0.5 m
4 towers with winds at 12-m AGL only
horz. turb. param. = meas. sigma theta
vert. turb. param.= similarity (P-G)

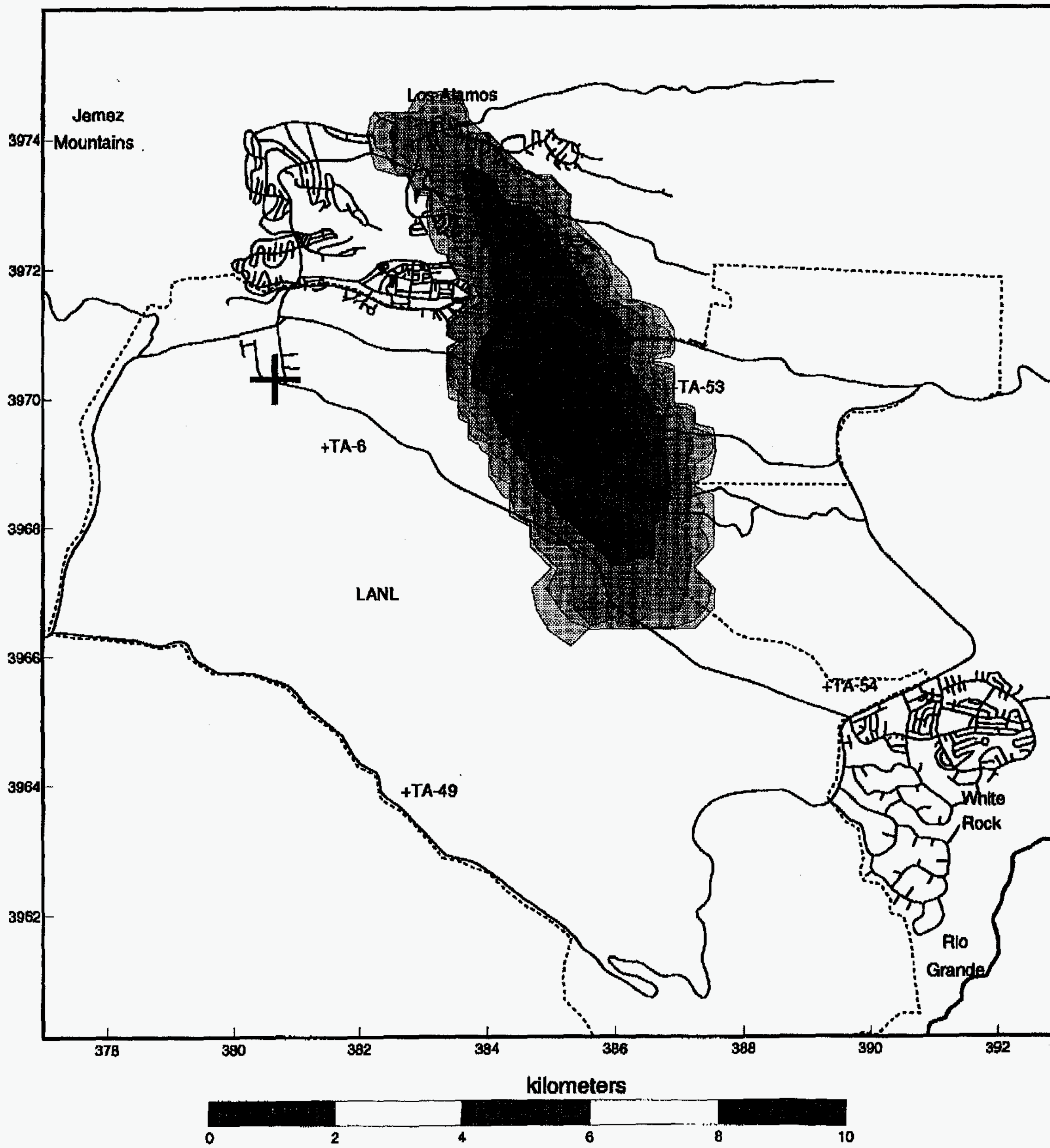
Contours:
(Level and Area Covered)

Level	Area Covered
> 1.00e-09 1/m3	2.74 sq km
> 1.00e-10 1/m3	7.45 sq km
> 1.00e-11 1/m3	10.54 sq km
> 1.00e-12 1/m3	12.85 sq km
> 1.00e-13 1/m3	13.90 sq km

Figure 5a.

50-m rel., all winds, meas. sig. theta

LANL 10 OCT 1994 vertical shear study



Plot Generation Time
19AUG97 23:34:00 UTC

Contour Type
Instantaneous air at 1.5 meters
10OCT94 05:00:00 UTC

Material
Hypothetical

Source Location (longitude, latitude)
106° 19' 19" W, 35° 52' 11" N

Source Location (x, y, projection)
380.67 km E, 3970.30 km N, UTM

Remarks
One hour unit release: 0300-0400 MST
1-m diam sphere, 50-m high, no exit ve
No deposition; Zo= 0.5 m
4 towers with winds at all levels
horz. turb. param. = meas. sigma theta
vert. turb. param.= similarity (P-G)

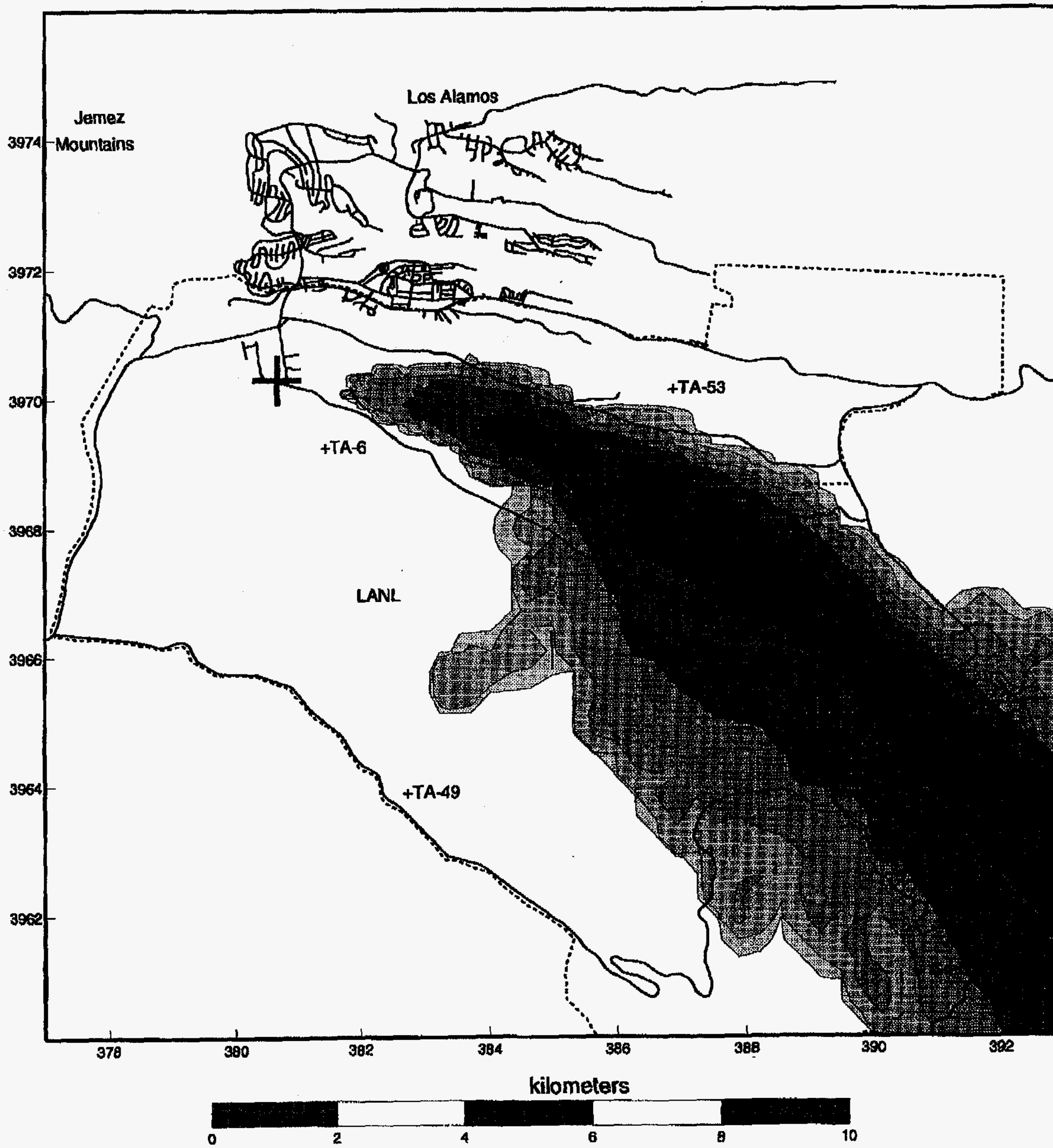
Contours:
(Level and Area Covered)

Level	Area Covered
> 1.00e-09 1/m3	3.03 sq km
> 1.00e-10 1/m3	10.30 sq km
> 1.00e-11 1/m3	17.64 sq km
> 1.00e-12 1/m3	21.22 sq km
> 1.00e-13 1/m3	23.08 sq km

Figure 5b.

50-m rel., 12-m winds, meas. sig. thet

LANL 10 OCT 1994 vertical shear study



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Contour Type	Integrated air at 1.5 meters 10OCT94 03:00:00 to 10OCT94 06:30:00 UTC
Material	Hypothetical
Source Location (longitude, latitude)	106° 19' 19" W, 35° 52' 11" N
Source Location (x, y, projection)	380.67 km E, 3970.30 km N, UTM
Remarks	One hour unit release: 0300-0400 MST 1-m sphere, 50-m high, no exit vel. No deposition; Zo= 0.5 m 4 towers with winds at 12-m AGL only horz. turb. param. = meas. sigma theta vert. turb. param.= similarity (P-G)

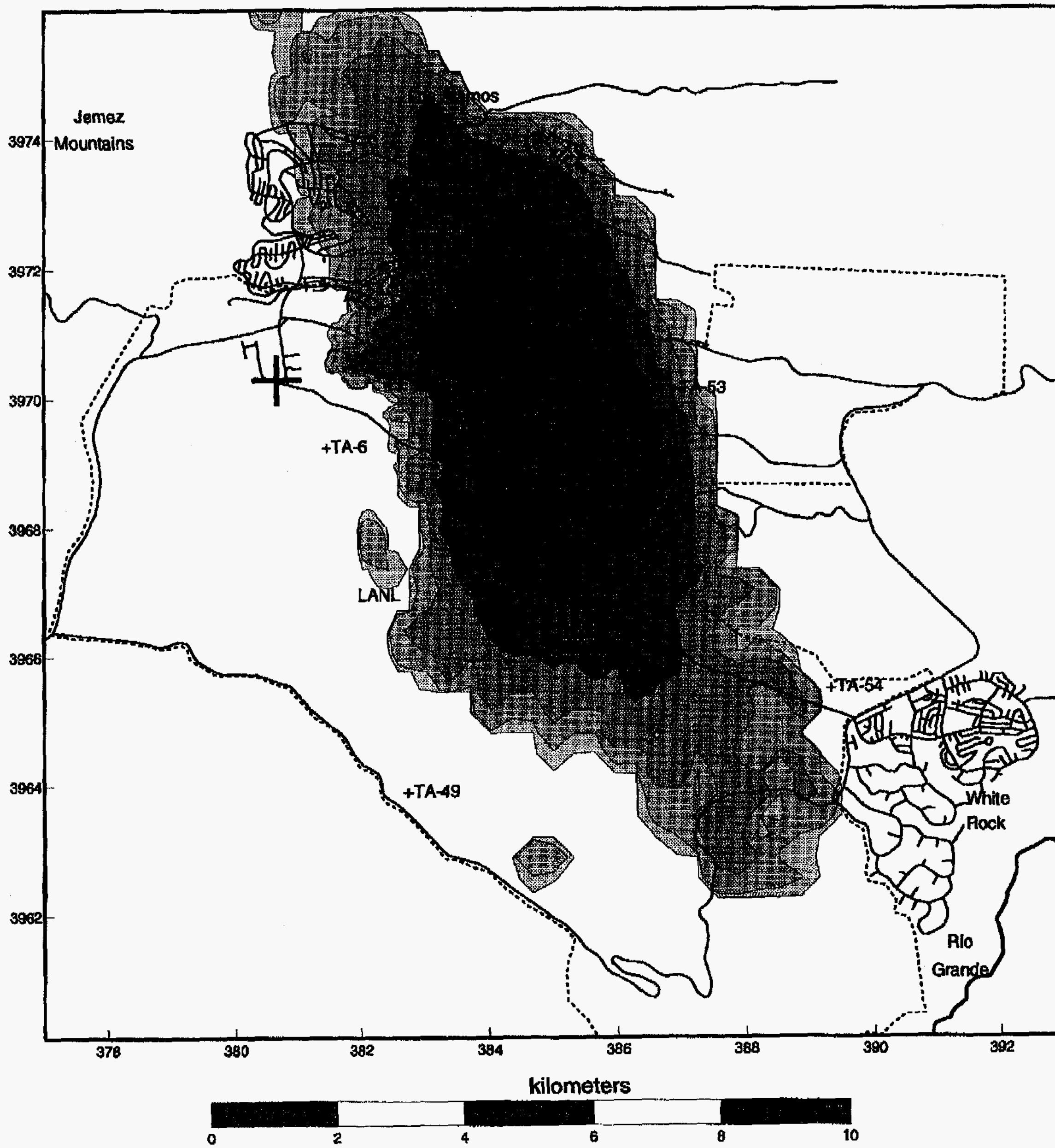
Contours:
(Level and Area Covered)

> 1.00e-06 s/m3	13.25 sq km
> 1.00e-07 s/m3	31.60 sq km
> 1.00e-08 s/m3	48.29 sq km
> 1.00e-09 s/m3	59.08 sq km
> 1.00e-10 s/m3	62.93 sq km

part 1 of Fig 6.

50-m rel., all winds, meas. sig. theta

LANL 10 OCT 1994 vertical shear study



Plot Generation Time
19AUG97 23:34:00 UTC

Contour Type
Integrated air at 1.5 meters
10OCT94 03:00:00 to 10OCT94 06:30:00 UTC

Material
Hypothetical

Source Location (longitude, latitude)
106° 19' 19" W, 35° 52' 11" N

Source Location (x, y, projection)
380.67 km E, 3970.30 km N, UTM

Remarks
One hour unit release: 0300-0400 MST
1-m diam sphere, 50-m high, no exit ve
No deposition; Zo= 0.5 m
4 towers with winds at all levels
horz. turb. param. = meas. sigma theta
vert. turb. param.= similarity (P-G)

Contours:
(Level and Area Covered)

> 1.00e-06 s/m3	14.47 sq km
> 1.00e-07 s/m3	29.49 sq km
> 1.00e-08 s/m3	46.02 sq km
> 1.00e-09 s/m3	58.42 sq km
> 1.00e-10 s/m3	63.71 sq km

part 2 of Fig 6.