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TOMEX: A Comparison of Lidar and Sounding Rocket Chemical Tracer

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TOMEX: A comparison of lidar and sounding rocket chemical tracer wind measurements

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[1] On October 26, 2000, a Black Brant V sounding rocket carrying a chemical tracer release was launched from the rocket range at White Sands, New Mexico, as part of the Turbulent Oxygen Mixing Experiment (TOMEX). The releases occurred approximately 150 km from the location of the Starfire Optical Range where the University of Illinois sodium lidar was operated to measure winds and temperatures in the mesosphere and lower thermosphere. The geometry for the experiment was such that the lidar beam was able to intersect the release point for the chemical tracer trail on the upleg part of the flight near an altitude of 95 km. In all, a total of five lidar beam directions were used to sample the region from approximately 85 to 105-km altitude in the vicinity of the releases. Combining the lidar Doppler velocity data from the various beam directions made it possible to produce profiles of vector horizontal winds that could be compared directly with the winds obtained from the triangulation of the chemical tracer trails. *INDEX TERMS:* 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques; 3360 Remote sensing; 3332 Mesospheric dynamics. **Citation:** Larsen, M. F., A. Z. Liu, R. L. Bishop, and J. H. Hecht, TOMEX: A comparison of lidar and sounding rocket chemical tracer wind measurements, *Geophys. Res. Lett.*, *30*(7), 1375, doi:10.1029/2002GL015678, 2003.

1. Introduction

[2] Over the last decade, improvements in laser and photodetector technology have made lidar measurements of minor constituents, such as sodium in the mesosphere and lower thermosphere region, increasingly routine. Although they are less common, due to the significant increase in cost and complexity, temperature and wind measurements with lidars in the same altitude range are also possible, the limiting factors being the abundance of the constituent which varies with height, the laser power, and the size of the telescope used for receiving. The University of Illinois sodium resonance lidar system was operated for several years at the Starfire Optical Range located near Albuquerque, New Mexico. The combination of the high-power laser system and the fully-steerable 3-m diameter telescope at the site produced a system with previously unrivaled sensitivity and resolution. The lidar has been used extensively to study waves, turbulence, and instabilities in the mesosphere and lower thermosphere, and earlier results have been described in the paper by *Gardner et al.* [2002], for example, which also discusses the capabilities of the system in more detail than we provide here.

[3] One problem with the lidar wind measurements and indeed with most wind measurements in the mesosphere is the difficulty of obtaining other measurements that can be used for comparisons or for calibration. The limited number of earlier comparisons include the study by *Franke et al.* [2001] in which lidar wind measurements made at the University of Illinois were compared with partial reflection drifts radar measurements made at the same location. The results showed general agreement in the tidal components that were extracted from each set of winds, but there were also significant differences in the instantaneous wind profiles obtained at any given time. The differences were explained, at least in part, by the fact that conditions for radar backscatter were best during the day when more ionization was present and poorest at night when the ionization densities were low, while the lidar obtained the best data at night. A more recent comparison was made between the lidar wind measurements and the winds from the University of Western Ontario meteor radar system which was operated at Starfire Optical Range for an extended period [*Liu et al.*, 2002]. In all, data from twenty nights were used for the comparison. The twenty-day hourly average winds for each hour of the night when both radar and lidar winds were available showed good agreement, but the comparison of the individual measurements showed a tendency for the radar to produce wind estimates that were generally smaller than the corresponding lidar wind estimates by a factor of almost two. The differences were attributed to the way that the instruments sample the atmosphere. During the 1998 Leonid meteor shower, *Grime et al.* [2000] compared the drift velocities of persistent meteor trails with the Doppler winds observed by the sodium lidar at Starfire Optical Range (SOR) and found that the wind measurements and drifts agreed within the measurement uncertainties.

[4] In addition to the remote sensing techniques, several in situ rocket techniques have also been used to measure winds in the mesosphere and lower thermosphere. The chemical tracer technique in particular has been used extensively [see, e.g., *Larsen*, 2002, and references therein]. *Lloyd et al.* [1972], *Bedinger* [1973], and *Rees et al.* [1976] compared TMA tracer wind measurements with meteor radar winds from locations in Australia, at Wallops Island in Virginia, and in the Hebrides, respectively. Such comparisons may not be entirely meaningful since the tracer wind measurements are made over a period of ten minutes or less while the meteor radars require upwards of an hour to produce a wind profile, but the agreement was not particularly good in any of those studies. *Schmidlin et al.* [1985],

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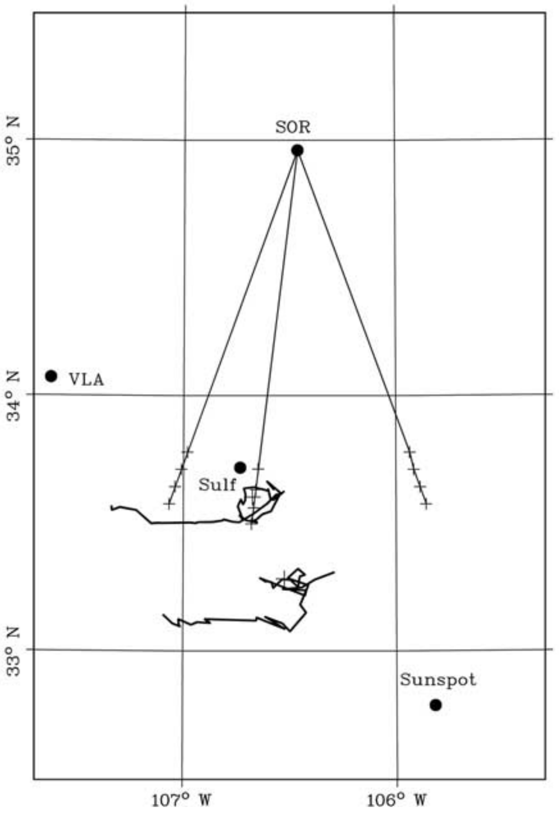

Figure 1. Locations of the launch site (Sulf), the lidar (SOR), and the ground-based camera sites (SOR, VLA, and Sunspot) used for the triangulation. The lidar beam directions are shown by the three lines that originate at SOR. The wind hodographs for the upleg and downleg TMA releases are also shown and give an indication of the trail locations approximately 5 min after the trails were initially released. The distance between the longitude lines is 111 km. The distance between the latitude lines is approximately 92 km.

on the other hand, compared in situ measurements from several different techniques, including chaff, falling spheres, and chemical tracers. The overall agreement between the measurements from the falling spheres and the chaff was better than between the measurements from those techniques and the chemical tracer, but the overlap between the measurements was generally limited to altitudes above 90 km where the chaff and falling sphere techniques have large uncertainties.

[5] In the recent Turbulent Oxygen Mixing Experiment (TOMEX) we had a unique opportunity to compare two sets of wind measurements that provide a more comparable sampling of the atmospheric winds than was possible in the earlier studies, specifically we were able to obtain lidar and chemical tracer wind measurements that were closely collocated in both space and time in the altitude range from 85 to 105 km.

2. Data Set Description and Wind Comparison

[6] The primary objective of TOMEX was to study the diffusion and mixing associated with unstable layers in the mesosphere and lower thermosphere region at midlatitudes. The primary ground-based measurements were provided by the University of Illinois sodium lidar at the Starfire Optical Range located near Albuquerque, New Mexico. The in situ measurements were made on a rocket launched from White Sands Missile Range and included photometers, ionization gauges, and upleg and downleg trimethyl aluminum (TMA) chemical tracer releases used to measure the winds and turbulence characteristics in the altitude range from approximately 85 to 140 km. The locations of the lidar (SOR) and the launch site (Sulf) are shown in Figure 1.

[7] Since the lidar measures the Doppler shift along the radial direction, measurements along several beam directions are required to obtain a profile of the vector winds. For TOMEX, one of the pointing directions was chosen to coincide with the initial release point of the upleg trail near an altitude of approximately 95 km. The other pointing directions were distributed as shown in Table 1. A total of five different pointing directions and three different azimuths were used. The azimuth directions are shown in Figure 1 by the three lines originating at SOR. Crosses indicate where the beams intersect altitudes of 85, 90, 95, and 100 km.

[8] The chemical tracer technique has been described extensively in the literature [see, e.g., *Larsen*, 2002]. In TOMEX trimethyl aluminum (TMA) trails were released on the upleg and downleg portions of the flight. TMA reacts with oxygen to produce a chemiluminescence that makes it possible to track the trails photographically over a period of 5–10 minutes or more. By using the star background and photographs from two or more sites, the location and movement of the trail can be determined, and the wind profiles can be determined. The triangulation was carried out with observations from SOR, from the Very Large Array (VLA) radio astronomy site, and from the Sunspot solar observatory site which are all shown in Figure 1.

[9] The first comparison uses the wind profile derived from the Beam 1 and 2 line-of-sight Doppler measurements which provide a sampling scheme that is similar to the sampling scheme used for typical lidar observations. A comparison of the zonal wind components from the upleg TMA wind profile and the lidar measurements derived in that way is shown in Figure 2. The launch occurred at 0957 UT. The upleg trail release started 67 seconds after launch and the downleg release 237 seconds after launch. The portion of the trail in the altitude range from 85 to 105 km, which is the focus of this comparison, was released over a period of about 20 sec. The triangulation was carried out with photographs covering a period of approximately 3 minutes. Both the triangulation and the lidar wind estimates assume that the vertical velocities are negligible. Vertical beam lidar measurements at Starfire show that the contribution to the standard deviation of the vertical velocities along the beam direction used in this study will be approximately 1 m s^{-1} which is negligible. Figure 2 shows the TMA zonal winds as the heavy line. Since the lidar was pointed directly at the predicted rocket trajectory, the lidar beam was moved to a

Table 1. Beam Directions Used for the Lidar Measurements

Beam	Azimuth	Elevation
1	160.00°	30.48°
2	200.00°	30.48°
3	187.02°	30.48°
4	187.02°	40.48°
5	187.02°	30.75°

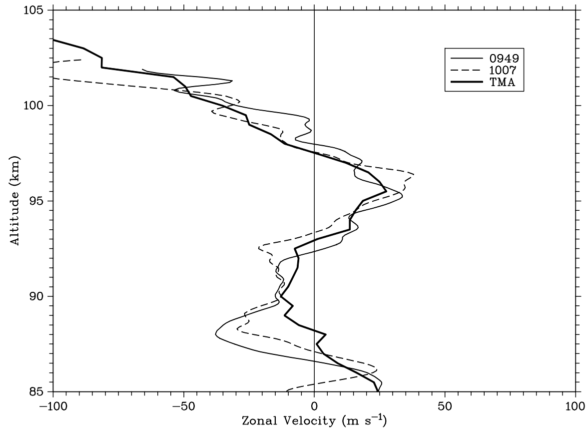

Figure 2. Comparison of the zonal wind component derived from the upleg TMA trail with the zonal wind component derived from the lidar radial Doppler velocity measurements in beams 1 and 2. The heavy line is the chemical tracer wind profile. The two lighter lines show the lidar winds for periods of ten minutes before and after the rocket launch.

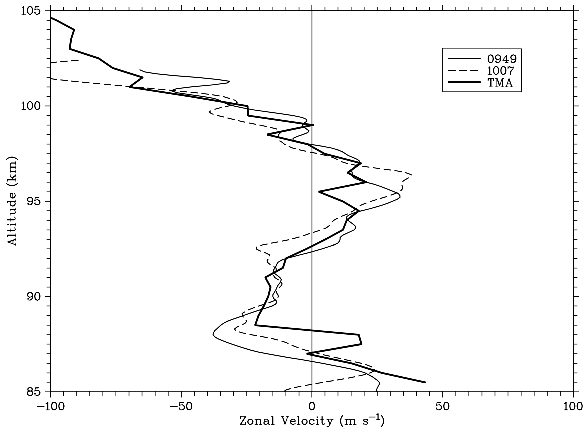

Figure 4. Comparison of the zonal wind component from the downleg TMA trail with the zonal wind from the lidar.

different azimuth at the time of launch to prevent possible damage to the rocket photometers. The two lighter curves show the lidar zonal wind components measured during a ten-minute period prior to the launch and during a ten-minute period following the launch. Comparisons of the lidar meridional wind components with the meridional component from the upleg trail are shown in Figure 3. Figure 4 and Figure 5 show similar comparisons for the downleg trail.

[10] The uncertainties in the wind estimates are due to a combination of instrument or triangulation errors and a combination of both temporal and spatial fluctuations in the medium itself. The various fluctuations cannot be separated unambiguously with the data that is available, but the combination of all contributions gives uncertainties of approximately 5–10 m s^{-1} for the chemical tracer measurements and 3–5 m s^{-1} for the lidar measurements. For the lidar the largest uncertainties are at the top and bottom of the measurement range. For the chemical tracer, the largest uncertainties are in the height ranges with the largest vertical shear.

[11] All the comparisons show good agreement in both the overall trends and in the magnitudes of the two sets of wind measurements. There is particularly good agreement between the zonal wind components with differences that are within the combined uncertainties of the two measurements above 90-km altitude. The complete chemical tracer wind profiles have maximum winds with wind speeds close to 150 m s^{-1} between 105 and 110-km altitude. Such wind maxima are a common feature of the more than 400 chemical tracer wind measurements made over the last four decades, as described by *Larsen* [2002]. The lidar data show good agreement with the chemical tracer wind measurements even in the altitude range where the wind speeds begin to increase significantly as the winds approach their maximum values in the lower thermosphere.

[12] The comparison of the meridional wind components is more complicated. The lidar and upleg TMA winds agree well below 95-km altitude. The lidar and downleg TMA winds agree well above 95 km. As shown in Figure 1, the lidar beams cut through the region diagonally so that the higher altitudes correspond to positions that are further

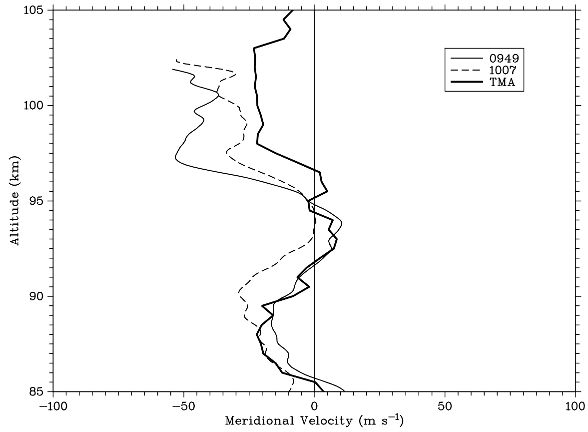

Figure 3. Comparison of the meridional wind component from the upleg TMA trail with the meridional wind from the lidar.

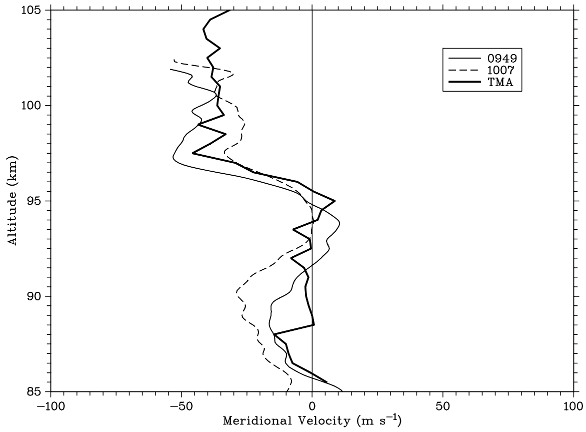

Figure 5. Comparison of the meridional wind component from the downleg TMA trail with the meridional wind from the lidar.

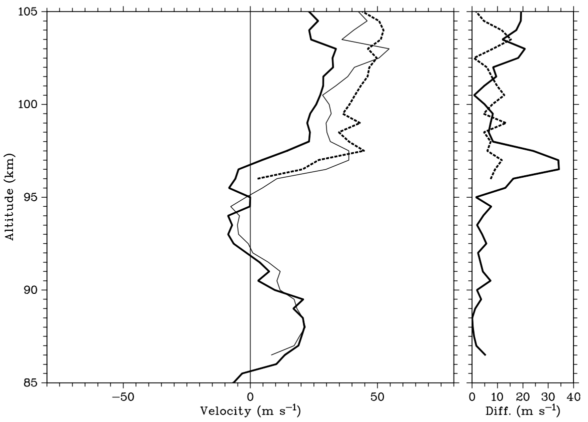

Figure 6. Comparison of the lidar winds measured along an azimuth of 187.02° from 095351 to 095524 just prior to the launch (light line) with the wind component from the upleg TMA along the same direction (heavy solid line). The heavy dashed line shows the corresponding wind component from the downleg trail for altitudes above 95 km. The differences between the lidar winds and the two sets of TMA winds are shown in the panel on the right.

south and the lower altitudes correspond to positions that are further north. The separation between the upleg and downleg trails is along a direction that is roughly from northwest to southeast. The meridional wind components obtained from the two trails clearly show a gradient along the direction separating the trails, consistent with the idea that the lidar wind profile reflects a horizontal, as well as a vertical, gradient in the meridional winds.

[13] Comparisons of the lidar and chemical tracer vector wind profiles require that measurements from several beam-pointing directions be combined so that temporal and spatial variations become a factor. Just prior to the launch, the lidar beam was pointed at an azimuth of 187.02° and an elevation angle of 30.75°. Figure 6 shows the comparison between the line-of-sight lidar Doppler velocity from that single measurement with the TMA wind component along the same azimuth direction. The heavy solid line shows the corresponding wind component extracted from the upleg trail. The heavy dashed line shows the downleg wind component along the same direction above 95 km. The differences between the lidar velocities and the two sets of chemical tracer velocities are shown in the panel on the righthand side of the figure. There is close agreement between the lidar and TMA winds below 95 km. Above 95 km, the lidar winds are generally larger than the winds from the upleg trail. The winds from the downleg trail above 95 km are generally larger than the lidar winds but closer in magnitude so that the lidar winds lie between the upleg and downleg values at the higher altitudes. All three curves show a similar variation with height.

3. Conclusion

[14] The TOMEX experiment has provided an unusual opportunity to compare two of the wind measurement techniques that have been used extensively for mesospheric wind measurements. The location of the Starfire Optical Range lidar site in the proximity of the White Sands Missile Range launch facility has made it possible to probe the region very close to where the chemical tracer TMA trail was released with the lidar. The excellent time and height resolution of the lidar measurements also made it possible to compare the two measurements much more directly than has been possible in some earlier studies. Since the trails provide an essentially instantaneous measurement over a period of a few minutes, statistical comparisons are not possible. Nonetheless, the two sets of wind profiles show excellent agreement both in terms of the magnitude and the vertical structure in the profiles.

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