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## Comparison of meteor radar and Na Doppler lidar measurements of winds in the mesopause region above Maui, Hawaii

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[1] Simultaneous sodium (Na) Doppler lidar and meteor radar measurements of horizontal winds in the mesopause region over Maui, Hawaii, were collected in July 2002 and October/November 2003. The coincident measurements span 96 hours and altitudes between 80 and 100 km. Statistical comparisons are carried out on radar/lidar winds with 1 hour and 4 km time and height resolution, respectively. The RMS radar/lidar wind component differences observed in this study are in the range 12–17 m/s at altitudes below 96 km. This is smaller than the RMS differences observed in a previous Na lidar and meteor radar comparison. Lidar wind component variances exceed radar variances, and radar/lidar covariance, is nearly equal to the radar variance. Excess variance observed by the lidar is consistent with the fact that the meteor radar cannot resolve wind perturbations with horizontal scales smaller than  $\sim 200$  km, whereas the lidar will respond to all horizontal scales. Close correspondence between the radar wind variance and radar/lidar covariance suggests that measurement errors associated with the radar winds are swamped by geophysical variation. Furthermore, the excess lidar variance exceeds lidar estimation errors by a large factor, indicating that the lidar measurement errors are also insignificant relative to geophysical variations. Together these observations suggest that the observed radar/lidar differences are a consequence of the different horizontal wave number filters associated with the techniques, and hence the differences are determined by the strength and shape of the horizontal wave number spectrum for wind perturbations at scales smaller than  $\sim 200$  km.

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### 1. Introduction

[2] Joint measurement campaigns involving all-sky airglow imagers, high-resolution Na Doppler lidar, and a meteor radar were carried out in July 2002 and October/November 2003 under the auspices of the Maui Mesosphere and Lower Thermosphere (Maui MALT) initiative. The meteor radar was deployed at Maui to provide temporally continuous measurements of mesopause region winds, which provide an essential context for interpreting lidar and airglow imager measurements of gravity waves propagating through the region.

[3] During these campaigns, the University of Illinois at Urbana-Champaign (UIUC) meteor radar and UIUC Na Doppler lidar operated simultaneously for approximately 96 nighttime hours, providing an opportunity to study the consistency between mesopause region winds measured by these instruments. This paper describes the characteristics of, and data analysis techniques employed by, the new

UIUC Maui meteor radar and a detailed statistical comparison of horizontal wind components measured by the Na Doppler lidar and meteor radar in the 80–100 km altitude range. The radar/lidar comparison reported here follows an earlier comparison between UIUC Na Doppler lidar winds and meteor radar winds [*Liu et al.*, 2002] collected at Starfire Optical Range (SOR) in New Mexico.

[4] This paper is organized as follows. Descriptions of the meteor radar and Na Doppler lidar are provided in section 2. Descriptive statistics summarizing the differences between the lidar and radar measurements of zonal and meridional wind components are presented in section 3. The results are interpreted in section 4. Finally, in section 5, the results are summarized and compared with earlier lidar/meteor radar comparison.

### 2. Instrument Descriptions

#### 2.1. Meteor Radar

[5] The UIUC Maui MALT meteor radar is located in Kihei on Maui, Hawaii, at 20.75°N, 156.43°W. The system

is a SKiYMET radar [Hocking *et al.*, 2001] operating at 40.92 MHz. A single three-element Yagi antenna directed toward the zenith is used to illuminate meteor trails. Meteor trail reflections are coherently detected on five three-element Yagi antennas oriented along two orthogonal baselines, with one antenna in the center of the array common to both baselines. On each baseline the outer antennas are separated from the center antenna by 1.5 and 2.0 wavelengths. This configuration minimizes antenna coupling, provides enough redundancy to unambiguously determine the azimuth and elevation of most echoes, and provides excellent angular resolution for position determination. The average transmitted power is approximately 170 W, resulting from a 13.3  $\mu$ s pulse length, 6 kW peak envelope power, and an interpulse period (IPP) of 466  $\mu$ s. Returns are sampled every 13.3  $\mu$ s, resulting in 2 km range resolution. The relatively short IPP causes meteor echoes to be aliased in range; however, the narrow height distribution of meteor echoes, combined with precise azimuth/elevation angle measurement, allows most range ambiguities to be resolved. Algorithms employed for determining meteor trail position and Doppler shift are described in detail in the work of Hocking *et al.* [2001].

[6] Wind velocities are estimated from the trail positions and Doppler shifts using a weighted least squares fit, assuming a constant wind vector composed of eastward and northward components. The vertical wind component is neglected. Thus the fitting procedure determines horizontal components ( $u$ ,  $v$ ) by minimizing the weighted residual

$$\chi^2 = \sum_i \left( \frac{v_r^i - ul^i - vm^i}{\sigma^i} \right)^2, \quad (1)$$

where  $v_r^i$  is the measured line-of-sight velocity, and  $l^i = \sin \theta^i \cos \phi^i$  and  $m^i = \sin \theta^i \sin \phi^i$  are components of a unit vector directed along the line-of-sight to the detected meteor trail. The zenith angle and azimuth angle of the  $i$ th meteor trail are denoted by  $\theta^i$  and  $\phi^i$ , respectively.

[7] The wind-vector fit is based on echoes collected within 1 hour time bins. The height resolution that can be achieved by the meteor radar is limited by uncertainty in the measured distance to the meteor trail and in the estimated zenith angle of the detected meteor trails. In terms of the RMS uncertainties in distance ( $\sigma_r$ ) and zenith angle ( $\sigma_\theta$ ), the RMS height uncertainty for a trail located at height  $h$  and zenith angle  $\theta$  is approximately

$$\sigma_h = \sqrt{\sigma_r^2 \cos^2(\theta) + h^2 \sigma_\theta^2 \tan^2(\theta)}. \quad (2)$$

[8] Assuming range errors uniformly distributed over  $\pm 2$  km, then  $\sigma_r = 1.33$  km. The RMS zenith angle error is expected to be  $\sim 1^\circ$ – $2^\circ$  [Jones *et al.*, 1988]. Most returns are detected from zenith angles in the range  $40^\circ$ – $60^\circ$ . For meteors at the most probable height (90 km) and zenith angle ( $50^\circ$ ), the height uncertainty is therefore  $\sim 2.2$ – $3.9$  km. The uncertainty is smaller for smaller zenith angles and is smallest for returns directed at the zenith. In view of these considerations the meteor data were binned into height bins of width 4 km. For the statistical comparisons discussed herein we estimated the wind components

at five heights using bins centered at altitudes of 82, 86, 90, 94, and 98 km. The bins corresponding to these altitudes do not overlap; this will ensure that statistical estimation errors at adjacent heights are independent and will simplify the interpretation of the results. Horizontal wind vectors were estimated when at least six meteor echoes were available in a 1 hour  $\times$  4 km time/height bin.

[9] Within a particular altitude bin the contribution from each trail is weighted by a term that depends on zenith angle,  $\theta^i$ , and distance,  $r^i$ . The inverse of the weighting coefficient, denoted by  $\sigma^i$  in equation (1), is defined by

$$(\sigma^i)^2 = (\sigma_s^2 \sigma_r^2 + \sigma_w^2) \cos^2 \theta^i + (r_i^2 \sigma_s^2 \sigma_\theta^2 + \sigma_u^2) \sin^2 \theta^i. \quad (3)$$

[10] In equation (3) the parameters  $r^i$  and  $\theta^i$  represent the measured range and zenith angle of the  $i$ th meteor echo. The  $\sigma_s$  on the right-hand side represent RMS uncertainties in measured range and zenith angle (in radians) of the meteor echo ( $\sigma_r$ ,  $\sigma_\theta$ ) and RMS spatial/temporal variations of the actual wind field with respect to the purely horizontal and uniform wind vector assumed for the fitting procedure ( $\sigma_u$ ,  $\sigma_w$ ,  $\sigma_s$ ).

[11] The error model, equation (3), is supposed to explain the variance of the observed meteor trail line-of-sight velocity around its expected value. The first term dominates for echoes detected at small zenith angles, where the measured line-of-sight trail velocity deviates from the value predicted by the constant horizontal wind model owing to contributions from the vertical wind component (with RMS variability  $\sigma_w$ ) and from error in determining the height of the echo in the presence of vertical wind shear. If the RMS wind shear for either component of the horizontal wind is denoted by  $\sigma_s$ , where  $\sigma_s^2 = \langle (\frac{\partial u}{\partial z})^2 \rangle = \langle (\frac{\partial v}{\partial z})^2 \rangle$ , and the uncertainty in measured distance to the meteor trail is  $\sigma_r$ , then the RMS residual due to height errors in the presence of wind shear is  $\sigma_s \sigma_r \cos \theta$ .

[12] The second term in equation (3) is dominant for echoes detected at large zenith angles, where residuals arise from deviations of the horizontal wind from the constant modeled value and from a height error/wind shear contribution arising from errors in the estimated zenith angle of the echo. We assume that the zonal and meridional wind have equal RMS deviations,  $\sigma_u$ , so that the RMS error due to the fluctuating component of the horizontal wind is  $\sigma_u \sin \theta$ . If the zenith angle associated with the meteor echo is estimated with RMS error  $\sigma_\theta$ , then the resulting height error is approximately  $r \sigma_\theta \sin \theta$ , so the product of height error and RMS wind shear is  $r \sigma_\theta \sigma_s \sin \theta$ .

[13] Several other error terms, all of which are expected to be relatively small compared to the terms discussed above, have been ignored. In particular, it should be noted that the RMS uncertainty of the estimated meteor trail radial velocity was not included in equation (3). This term is calculated in practice from the radial velocities obtained using each of the five receiver channels. When the RMS uncertainty of the radial velocity exceeds 7 m/s, the meteor echo is discarded. The median RMS uncertainty of the remaining radial velocity measurements, which are used for wind estimation, is a few m/s. Hence this term is negligible compared to the terms already included in equation (3). The numerical values of the weighting function

**Table 1.** Parameters Used in the Error Model<sup>a</sup>

Parameter	Value
$\sigma_\theta$	2°
$\sigma_r$	1.33 km
$\sigma_u$	10 m/s
$\sigma_w$	1 m/s
$\sigma_S$	7 m/s/km

<sup>a</sup>See equation (3).

parameters employed for our fits are summarized in Table 1. The RMS zenith angle and range errors were determined as described earlier. The RMS vertical and horizontal winds and RMS wind shear were adjusted to simultaneously minimize the RMS differences between radar and lidar winds and to normalize the mean square residual to unity, i.e., we force  $\langle \chi^2 \rangle \simeq 1$ . It is important to note that the numerical values used for these parameters were adjusted to force the error model into compliance with the observed RMS residuals by requiring that the ensemble mean value of  $\chi^2$ , taken over the entire data set, is approximately unity, i.e.,  $\langle \chi^2 \rangle \simeq 1$ . As such, the numerical values  $\sigma_w$ ,  $\sigma_u$ , and  $\sigma_S$  given in Table 1 should not be taken as formal estimates of these parameters. We have carried out numerous comparisons between the lidar wind and the radar wind and have verified that the weighting function described here results in smaller RMS radar/lidar differences than does either an unweighted fit with fixed zenith angle limits or fits based on equation (3) but with radically different numerical values for the parameters given in Table 1.

## 2.2. Na Doppler Lidar

[14] The UIUC Na wind/temperature lidar is installed at the Air Force Research Laboratory AEOS facility on Maui, at the peak of Haleakala, at coordinates 20.71°N, 156.26°W. The laser is coupled to a 3.7 m steerable astronomical telescope through the coude path so that the beam can be pointed at any direction. A 0.6 m diameter portion of the telescope primary mirror is used to project the laser beam, while the remainder is used for collecting backscattered light and for focusing it onto the detector. The beam divergence is approximately 0.4 mrad, which produces a beam diameter (full width at  $e^{-2}$ ) of 40 m at a range of 100 km. The laser transmitter is pulsed at 50 pps, and the measured laser output power varies between 1 and 2 W. The laser beam is coupled to the telescope primary mirror through the coude optical system, which is also shared with the lidar detector. We estimate that the coupling efficiency is at least 50%, so that the actual laser power transmitted into the atmosphere varies between about 0.5 and 1 W. In this configuration, temperature and radial wind can be measured along the laser beam. The lidar is pointed at zenith (Z) and 30° off-zenith to the north (N), south (S), east (E), and west (W) in the following sequence ZNEZSW. At each position, backscattered photocount profiles are obtained at three frequencies (peak, plus, and minus), with a 90 s integration time and 24 m range resolution. The laser frequencies are controlled by an acousto-optic modulator, and the frequency is shifted every 50 pulses, or once per second. Approximately 30 s are required to steer the telescope to the next position. This six-position sequence is completed about every 12 min so the complete wind and temperature field can be derived every 6 min. To increase signal-to-noise ratio,

the raw wind and temperature data are derived at a height resolution of 480 m. The horizontal wind at each direction (NSEW) was derived by dividing the radial wind by  $\sin(30^\circ)$ . The vertical wind component in the radial wind is assumed to be negligible.

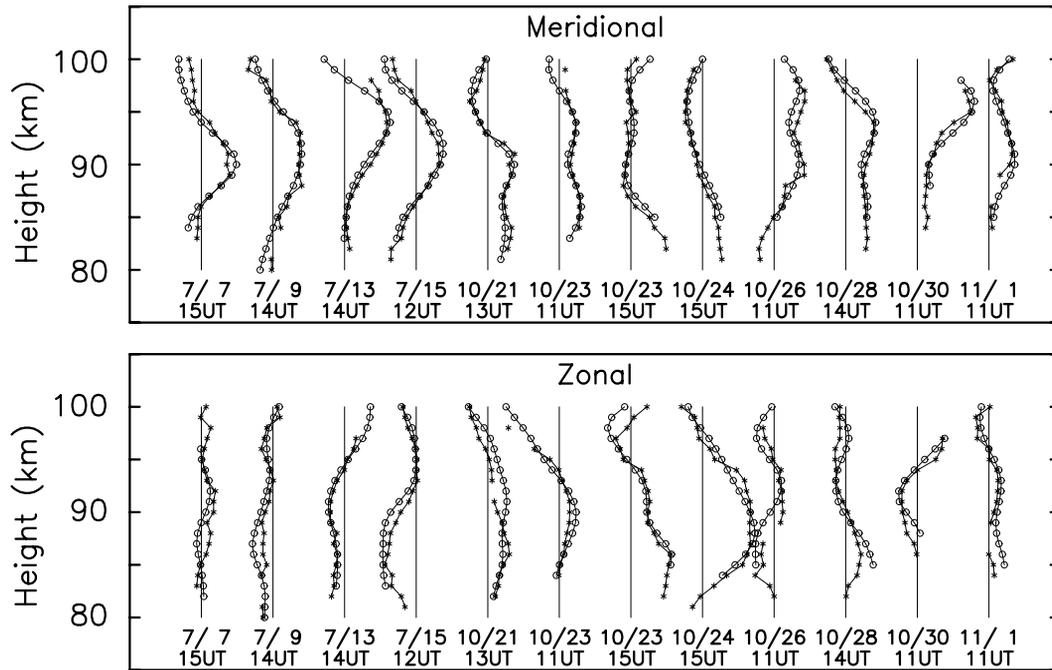
## 3. Results From the 2002 and 2003 Campaigns

[15] Simultaneous radar/lidar wind measurements are available for five nights in July 2002 and for seven nights in October/November 2003. Approximately 96 hours of simultaneous wind measurements are available. For statistical comparisons with the radar winds the time and height resolution of the lidar winds were degraded with filters to match those of the meteor radar winds. This was accomplished by averaging the lidar winds in 1 hour blocks, and by averaging the data in height over bins of width 4 km, centered at the same altitudes used for estimating the radar winds. While it is possible to match the temporal and height resolutions of the two instruments using these filters, the two instruments sample the wind field differently in the horizontal plane, and hence the instruments have significantly different effective horizontal wave number response functions. The lidar samples the line-of-sight wind component at five points, and each sample represents a spatial average over the spot illuminated by the lidar, which has a diameter of approximately 40 m. The meteor radar estimates winds using meteor trail echoes distributed randomly over a horizontal region with diameter  $\sim 200$  km. As such, wind perturbations with scales comparable to, or smaller than, this dimension will not be resolved by the radar. Therefore the portion of the horizontal wave number spectrum for horizontal wind perturbations corresponding to scales smaller than  $\sim 200$  km will contribute to observed variance in the lidar winds, but not to the radar winds. In the absence of instrumental measurement errors the lidar winds should exhibit more variance than the radar winds, and the excess lidar variance will correspond to the variance expected for radar/lidar wind differences. Instrumental measurement errors will add additional contributions to the variance of the radar/lidar wind difference. We shall examine the relative importance of contributions from measurement errors and difference in horizontal wave number response functions later in the paper.

[16] To illustrate the nature of the data set, sample height profiles of meridional and zonal wind components measured simultaneously by the two instruments are plotted in Figure 1, where the lidar profiles are marked with circles and the radar measurements are plotted with asterisks. As noted earlier, the profiles have 1 hour and 4 km time and height resolution, respectively. The profiles have been oversampled at a 1 km height interval for these plots. In general, strong correspondence between the meteor and lidar wind profiles is evident.

[17] Scatterplots of all coincident radar/lidar winds from all five altitude bins are plotted in Figure 2, and histograms of lidar/radar wind component differences are shown in Figure 3. The statistical moments of the joint data set are summarized in Table 2.

[18] Referring to Table 2, the mean radar/lidar wind component differences are 0.4 m/s (meridional) and 0.6 m/s (zonal). Since the difference histograms shown in



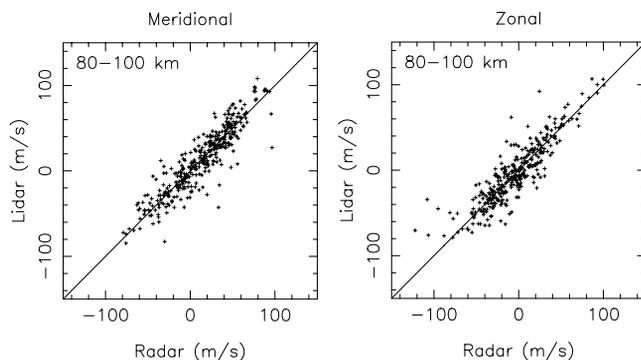
**Figure 1.** Sample (top) meridional and (bottom) zonal wind profiles collected during the July 2002 and October 2003 campaigns. Lidar profiles are marked with circles, and radar profiles are marked with asterisks. The profiles are scaled such that the horizontal distance between vertical lines corresponds to 150 m/s.

Figure 3 indicate some noticeable deviation from the normal distribution (plotted with the smooth line), we determined 99% confidence intervals for the mean differences using the bootstrap procedure described in the work of *Efron and Tibshirani* [1998]. In particular, we used 500 bootstrap replications and determined the 0.5 and 99.5 percentiles of the bootstrap distribution of radar/lidar wind component mean differences. The confidence intervals are  $[-1.6, 2.4 \text{ m/s}]$  (meridional) and  $[-1.5, 2.9 \text{ m/s}]$  (zonal). In both cases the 99% confidence interval for the radar/lidar mean differences includes zero, indicating that there is no significant difference between the radar and lidar mean winds.

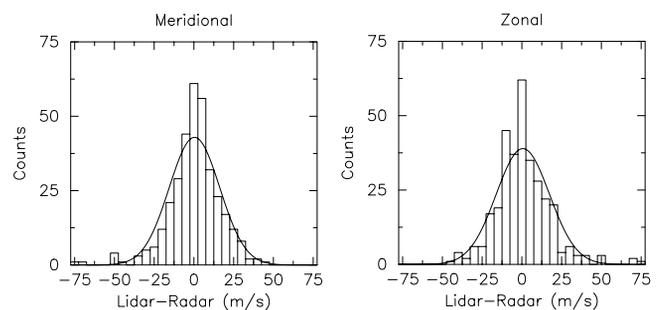
[19] The median radar/lidar differences were found to be 0.8 m/s (meridional) and  $-0.2 \text{ m/s}$  (zonal). The Wilcoxin signed-rank sum test was used to test the hypothesis that the observed median differences arise from a population with

nonzero median [*Wilcoxin*, 1992]. The Wilcoxin test indicates that the observed medians are not significantly different from zero at the 5% level (the probabilities calculated using the Wilcoxin test were 22% (meridional) and 78% (zonal)). Thus we conclude that the mean and median differences are not significantly different from zero.

[20] The variance of the lidar wind components are 12% (meridional) and 7% (zonal) larger than the corresponding radar values. Radar/lidar covariances are nearly equal to the radar variances, resulting in a correlation of 0.91 between the radar/lidar meridional components and 0.89 between the zonal components. The median absolute value of the radar/lidar wind component difference is 8.4 m/s (meridional) and 9.0 m/s (zonal), i.e., half of all coincident radar/lidar



**Figure 2.** Scatterplots for all coincident radar and lidar measurements in 80–100 km altitude range.



**Figure 3.** Histograms of radar/lidar wind component differences within the 80–100 km altitude range. See Table 2 for summary statistics of the wind component differences. The smooth curves represent normal distributions with mean and variance equal to the sample mean and variance.

**Table 2.** Statistical Moments of Horizontal Wind Components for All Coincident Data Points in the 82–98 km Altitude Range<sup>a</sup>

Meridional Component	Value	Zonal Component	Value
number of coincident samples	341	number of coincident samples	326
$\langle v_R^i \rangle$	13.1 m/s	$\langle u_R^i \rangle$	-3.8 m/s
$\langle v_L^i \rangle$	12.7 m/s	$\langle u_L^i \rangle$	-4.4 m/s
median[ $v_L^i - v_R^i$ ]	0.8 m/s	median[ $u_L^i - u_R^i$ ]	-0.2 m/s
Var[ $v_R^i$ ]	1268 m <sup>2</sup> /s <sup>2</sup>	Var[ $u_R^i$ ]	1217 m <sup>2</sup> /s <sup>2</sup>
Var[ $v_L^i$ ]	1420 m <sup>2</sup> /s <sup>2</sup>	Var[ $u_L^i$ ]	1308 m <sup>2</sup> /s <sup>2</sup>
Cov[ $v_R^i, v_L^i$ ]	1218 m <sup>2</sup> /s <sup>2</sup>	Cov[ $u_R^i, u_L^i$ ]	1123 m <sup>2</sup> /s <sup>2</sup>
$\gamma(v_R^i, v_L^i)$	0.91	$\gamma(u_R^i, u_L^i)$	0.89
$\sqrt{\langle (v_R^i - v_L^i)^2 \rangle}$	15.9 m/s	$\sqrt{\langle (u_R^i - u_L^i)^2 \rangle}$	16.7 m/s
median[ $ v_R^i - v_L^i $ ]	8.4 m/s	median[ $ u_R^i - u_L^i $ ]	9.0 m/s

<sup>a</sup>The angle brackets represent an average over all coincident radar/lidar samples. Symbols  $u_L$  and  $u_R$  represent the zonal component of lidar and radar winds, respectively, whereas  $v_L$  and  $v_R$  represent the meridional components. The symbol  $\gamma$  is used to represent the correlation coefficients, i.e.,  $\gamma(x, y) = \text{Cov}(x, y) / \sqrt{\text{Var}[x]\text{Var}[y]}$ .

meridional (zonal) wind component pairs differ by more/less than 8.4 m/s (9.0 m/s). The RMS radar/lidar differences are approximately 16 m/s (meridional) and 17 m/s (zonal).

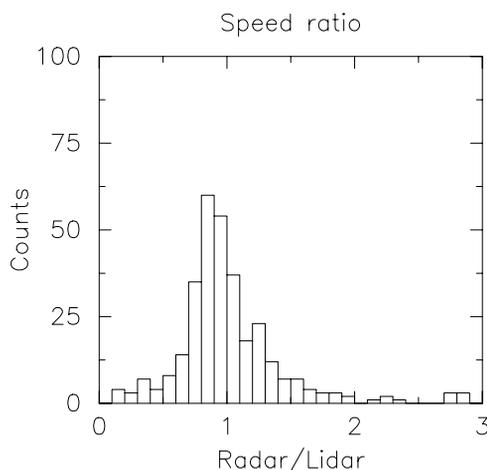
[21] So far, the zonal and meridional components of the wind have been compared separately. It is also of interest to compare the radar and lidar winds in terms of speed (magnitude) and direction. Figure 4 shows the distribution of the radar/lidar wind speed ratio. The median of this distribution is 0.95. A median of 1.0 would indicate that radar wind speed exceeded the lidar wind speed in 50% of the measurements (and vice versa). To test whether or not the observed value is significantly different from 1.0, we applied the Wilcoxon signed-rank sum test to the quantity  $1.0 - (\text{speed ratio})$ , which would have a median of zero if the median speed ratio is 1.0. The test indicates that the observed value of 0.95 is not significantly different from 1.0 at the 5% level.

[22] Figure 5 shows the distribution of radar/lidar wind direction differences in degrees. The mean wind direction difference is  $3.4^\circ$ , and a 99% bootstrap confidence interval is  $[-6.3^\circ, 13.8^\circ]$ . The median of the direction difference distribution is  $-2.8^\circ$ . A Wilcoxon test indicates that the median difference is not significant at the 5% level. The actual probability of observing a median difference this

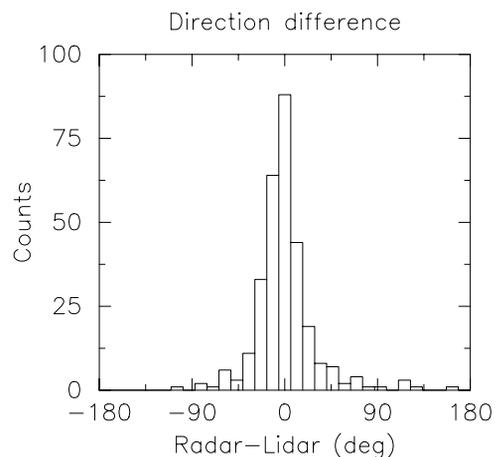
large or larger, if the underlying population median is  $0^\circ$ , is 15%. Hence we conclude that the wind direction differences are not significantly different from  $0^\circ$ .

[23] The summary statistics described above include data from all altitudes. The altitude dependence of the statistics is summarized next. Figure 6 shows how the variances and covariances depend on altitude in the five layers spanning 80–100 km. The number of radar/lidar sample pairs represented in these statistics is between 82 and 96 in the middle three layers but only 12 and 55 at the lowest and highest layers, respectively. Thus the results for the lowest layer have relatively large uncertainty. Note again that the lidar variance exceeds the radar variance at most altitudes and that the radar/lidar covariance is nearly equal to the radar variance at all altitudes. Figure 7 shows the radar/lidar correlation coefficients derived from the data plotted in Figure 6, illustrates that correlation is high at all altitudes, and is in the range 0.79–0.94.

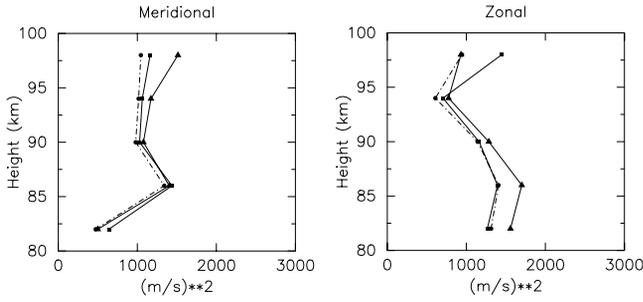
[24] Finally, Figure 8 shows the median absolute value of the radar/lidar wind differences (plotted with filled triangles) and RMS difference (plotted with filled squares). The median absolute differences are 7–8 m/s (meridional) and



**Figure 4.** Histograms of radar/lidar wind speed ratio within the 80–100 km altitude range. The median speed ratio is 0.95.



**Figure 5.** Histograms of radar/lidar wind vector direction differences, in degrees, within the 80–100 km altitude range. The mean direction difference is  $-3.4^\circ$ , and a 99% confidence interval derived using a bootstrap calculation is  $[-6.3^\circ, 13.8^\circ]$ .

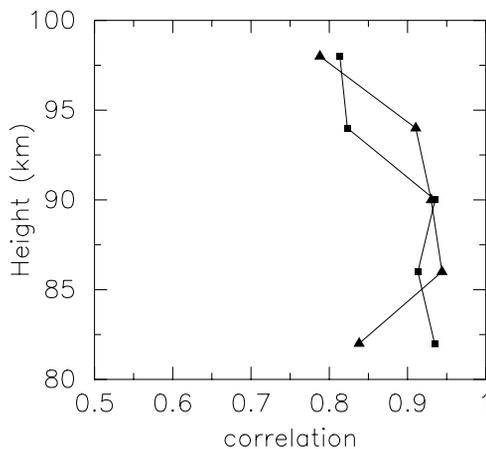


**Figure 6.** Variance of radar (solid line with squares) and lidar (solid line with triangles) winds and the covariance (dash-dot line with circles) as a function of height.

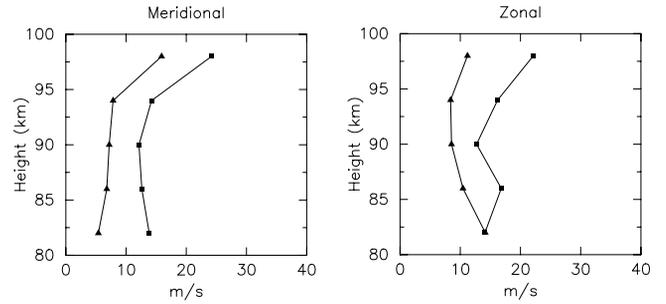
8–11 m/s (zonal) at the three central height bins spanning 84–96 km. Somewhat larger values appear for the meridional component at the highest altitude bin (96–100 km) and for the zonal component at the lowest altitude bin (80–84 km). Within the 80–96 km height range the RMS differences are  $\sim 12$ –14 and  $\sim 13$ –17 m/s. Higher RMS differences are observed at the highest altitude bin (96–100 km).

#### 4. Interpretation

[25] The lidar photocounts are highest just above 90 km, and the meteor echo occurrence peaks at 90 km. Thus winds estimated by the two instruments will have the smallest instrumental errors near 90 km, and the errors will tend to be larger at significantly lower or higher altitudes. In addition, it is known that spatial and temporal fluctuations of the wind field associated with gravity waves tend to increase with altitude, especially above 96 km [e.g., Gardner *et al.*, 2002]. It is likely that these effects account for the fact that the radar/lidar median and RMS differences tend to be smallest, and the correlation coefficients largest, within the central height bin (spanning 88–92 km) and for the fact that the RMS difference increases more quickly above that range than below it. Additional physical mechanisms related to electrodynamic may operate to structure and move meteor trails at altitudes near and above 95 km;



**Figure 7.** Correlation coefficient for meridional (triangles) and zonal (squares) radar/lidar wind components as a function of height.



**Figure 8.** Median absolute difference (triangles) and RMS difference (squares) between lidar and radar wind components versus height.

they could also contribute to the larger RMS differences observed at the highest bin [e.g., Oppenheim *et al.*, 2003].

[26] In the combined (as summarized in Table 2) and height-sorted data sets (as summarized in Figure 6), the radar/lidar wind component covariances are very nearly equal to the radar variances. In addition, in the combined data set, the lidar variance exceeds the radar variance by 12% (meridional) and 7% (zonal). When sorted by height, the lidar variance exceeds the radar variance in four out of five height bins for both meridional and zonal components by as much as 20%. These characteristics are consistent with the results and interpretation published by Liu *et al.* [2002] for the earlier comparison at SOR. In that study, zonal and meridional components were compared separately at two heights, and the lidar variance exceeded the radar variance by 14–29% in three out of the four cases. As noted earlier, and discussed in the work of Liu *et al.*, the larger variance of lidar winds is consistent with the fact that the lidar technique is sensitive to wind perturbations within a larger range of horizontal wave numbers. This situation can be modeled by decomposing the fluctuating (zero mean) component of the wind field into two statistically independent components, one having relatively large horizontal scale size ( $v_{ls}$ ) that is resolved by both the radar and lidar and the other having a small horizontal scale size that is resolved only by the lidar ( $v_{ss}$ ), i.e., the estimated radar and lidar wind components may be written as follows:

$$v_R = v_{ls} + \delta v_R \quad (4)$$

and

$$v_L = v_{ls} + v_{ss} + \delta v_L, \quad (5)$$

where  $\delta v_R$  and  $\delta v_L$  represent radar and lidar estimation errors, respectively. Assuming that all terms have zero mean, then variances are equal to mean square values, and the radar variance is

$$\langle v_R^2 \rangle = \langle v_{ls}^2 \rangle + \langle \delta v_R^2 \rangle. \quad (6)$$

The lidar variance is

$$\langle v_L^2 \rangle = \langle v_{ls}^2 \rangle + \langle v_{ss}^2 \rangle + \langle \delta v_L^2 \rangle, \quad (7)$$

and the radar/lidar covariance is

$$\langle v_R v_L \rangle = \langle v_{ls}^2 \rangle. \quad (8)$$

[27] The measured radar variance is nearly equal to radar/lidar covariance at all altitudes, which implies that  $\langle v_{ls}^2 \rangle \gg \langle \delta v_R^2 \rangle$ , i.e., radar variance is dominated by large-scale geophysical wind fluctuations, which are also sensed by the lidar. The small difference between the radar variance and the radar/lidar covariance reflects the mean square radar estimation error ( $\langle \delta v_R^2 \rangle$ ). For the combined data set the radar variance exceeds the radar/lidar covariance by  $50 \text{ m}^2/\text{s}^2$  (meridional) and  $94 \text{ m}^2/\text{s}^2$  (zonal). The inferred estimation errors are  $\sqrt{50} \simeq 7.1 \text{ m/s}$  (meridional) and  $\sqrt{94} \simeq 9.7 \text{ m/s}$  (zonal). These values are remarkably consistent with the median standard errors derived independently from the weighted least squares fitting procedure, which are  $7.6 \text{ m/s}$  (meridional) and  $9.3 \text{ m/s}$  (zonal).

[28] When all altitudes are considered together, the lidar variance exceeds the radar/lidar covariance by  $202 \text{ m}^2/\text{s}^2$  (meridional) and  $185 \text{ m}^2/\text{s}^2$  (zonal). Since the median lidar estimation errors are only  $\sim 3\text{--}4 \text{ m/s}$ , the excess lidar variance is almost entirely due to geophysical wind fluctuations with horizontal scales that are smaller than  $\sim 200 \text{ km}$ , which are too small to be resolved by the radar. Our results suggest that the variance of this small-scale component of the horizontal wave number spectrum is  $\langle v_{ss}^2 \rangle \simeq 200 \text{ m}^2/\text{s}^2$ .

[29] We conclude our interpretation of the results with a summary of the error budget for the radar/lidar differences. According to our model for the second moments of the radar and lidar winds, the RMS difference is

$$\sqrt{\langle (v_L - v_R)^2 \rangle} = \sqrt{\langle v_{ss}^2 \rangle + \langle \delta_R^2 \rangle + \langle \delta_L^2 \rangle}. \quad (9)$$

We have shown that the dominant term in this error budget is  $\langle v_{ss}^2 \rangle$ , which was estimated to be  $\sim 200 \text{ m}^2/\text{s}^2$ . Thus, even in the absence of the estimation errors associated with the radar and lidar instruments, an RMS difference  $\sim \sqrt{200} = 14 \text{ m/s}$  is expected, owing to the inherent mismatch between the horizontal wave number response functions. Taking the medians of the standard errors provided by the radar and lidar wind estimation algorithms as representative values for the mean square radar and lidar estimation errors, the estimation errors are  $8^2$  and  $3.5^2 \text{ m}^2/\text{s}^2$  for the radar and lidar, respectively. When these contributions are added, the expected RMS difference increases to  $\sim 16.6 \text{ m/s}$ , commensurate with our observations.

## 5. Summary and Conclusion

[30] In summary, the joint radar and lidar data set has been examined carefully for evidence of significant differences in mean meridional and zonal wind components and wind direction. No statistically significant differences were discovered. The distribution of the radar/lidar wind speed ratio was examined for evidence of any tendency for one instrument to systematically measure larger or smaller wind speeds relative to the other, and no evidence for such a tendency was found. The comparison presented herein suggests that the RMS differences observed between radar and lidar wind measurements are mainly because the instruments view the wind field through different horizontal wave number filters. The magnitude of the differences reflects the spectral density of the horizontal wave number spectrum at scales smaller than  $\sim 200 \text{ km}$  and within the range of

temporal frequencies and vertical wave numbers resolved by the 1 hour and 4 km time and altitude resolution of the data.

[31] The RMS radar/lidar wind differences are smaller than those reported for the earlier comparison between the UIUC Na lidar and a meteor radar. In particular, *Liu et al.* [2002] reported an average RMS difference of  $20 \text{ m/s}$  at 86 and 93 km and correlation coefficients in the range  $0.63\text{--}0.70$  at these two altitudes for comparisons at SOR in New Mexico. In contrast, the RMS difference reported here is in the range  $12\text{--}17 \text{ m/s}$  in the  $80\text{--}96 \text{ km}$  range, and correlations are in the range  $0.79\text{--}0.94$  at these altitudes. The meteor radar at Maui operates in a more favorable radio-frequency environment than the radar at SOR, with less interference and correspondingly higher meteor echo occurrence rates. Also, the lidar was pointed only  $10^\circ$  degrees off of zenith for the SOR campaign, whereas the off-zenith angle was  $30^\circ$  at Maui. For equal photon counts the instrumental errors will therefore be larger by  $\sin(30^\circ)/\sin(10^\circ) = 2.9$  at SOR. Generally, photon counts per pulse were larger at SOR by a factor of  $\sim 3\text{--}5$ , but the pulse repetition rate was 60% smaller. Overall, the instrumental errors were  $\sim 2$  times larger at SOR. Thus both instruments achieved smaller estimation errors at Maui. Another factor which undoubtedly acts to increase the correlation coefficients at Maui is the large amplitude of the diurnal and semidiurnal oscillations at this location relative to SOR. This provides a large common-mode signal for the radar and lidar, which will tend to decrease the decorrelating influence of estimation errors and wind perturbations with relatively small horizontal scales that can be resolved by the lidar but not the radar.

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