*In this document, the reviewer's comments are in black, the authors' responses are in red.*

The authors thank the reviewer for their thoughtful and productive comments.

**General Comments:**

This manuscript uses three months of data collected during the XPIA field campaign from 4 lidars and sonic anemometers on a 300m tower to calculate turbulence dissipation rates. The manuscript furthers a method of calculating epsilon from O' Connor et al 2010, using the line of sight velocity spectra, and conducts an error analysis to determine the time scale that produces the most accurate turbulence dissipation rates. The minimum mean absolute error is determined for stable, unstable, and neutral conditions with good agreement with sonics, particularly when averaged to 30-minutes. These results are then compared for different heights, wind speeds, Obukhov length, and during one nocturnal low-level jet case to understand the variability of turbulence dissipation rates in a large range of conditions.

Overall, this is a well-conducted error analysis that allows for further analysis of variability of a difficult-to-measure quantity. My major concern comes from the fact that in situ observations are necessary for this analysis to be reasonably, so the extension of the method to a broad number of lidar sites without sonic anemometers seems unlikely.

Thank you for finding our work interesting and useful!

I recommend publication of this manuscript after major revisions, as listed below.

**Specific Comments:**

The fact that on many plots the v1s are not included is worrisome; looks like only the good results are shown. A short sentence that results are similar is insufficient. It deserves a short discussion on the differences, benefits and drawbacks of each of the systems and why there is expected to be some variation (even if small).
The results for the v1s are shown in Figures 6, 7, but not in Figures 9, 10, 11, 12. This choice was due to the fact that adding other lines and shaded areas to plots that are already really dense would have substantially increased the difficulty for a reader to read the plots, while not providing any new substantial knowledge as the results for the v1s are very similar to what obtained for the v2. However, all the plots for the v1s are included in the Supplementary Material (except for the correspondent of Figure 10 due to data contamination for the v1s at some heights for hard strikes). Thank you for noticing that the fact that all the plots for the v1s can be found in the Supplement was not pointed out in a clear enough way in the manuscript.

In Section 5, the presentation of Figure 9 and its caption already included sentences to refer to the Supplementary Material for the plot for the WINDCUBE v1s. In the description of Figure 11 we have now included the following sentence: "The Supplementary Material includes the plot for the WINDCUBE v1s, which provide results very similar to what shown here". Also, the caption of the Figure now includes: "Results from the two WINDCUBE v1s are included in the Supplementary Material". In a similar way, the introduction of Figure 12 now includes the following: "(results for the WINDCUBE v1s are included in the Supplementary Material as very similar to what is found for the v2)". And the caption of the Figure now includes: "Results from the two WINDCUBE v1s are included in the Supplementary Material."

We expect to find the main variations in the results between the WINDCUBE lidars and the Halo lidar, given the difference in the scan pattern used (4,5 beams for the v1s, v2, while vertical stare for the Halo). To make this clear, we have included and modified the following sentences in Section 3.2:

"For the WINDCUBE lidars, the variance of the observed line-of-sight velocity $\sigma_v^2$ can be calculated as average from all the beams. In doing so, we include turbulence contributions from both the horizontal and vertical dimensions, and we make the limiting (Kaimal et al. 1972, Mann 1994) assumption of isotropic turbulence. For the Halo Streamline lidar, which operated in a vertical stare mode, $\sigma_v^2$ is calculated from the vertically pointing beam, and therefore $\epsilon$ will strictly include turbulence contributions only in the vertical dimension, thus possibly determining different values compared to what is retrieved from the WINDCUBE lidars.

Another difference due to the different scan patterns used by the considered lidars is related to the determination of the horizontal wind speed U. For the WINDCUBE lidars, U can be derived from the line-of-sight velocity measurements from the different beams, with the assumption of horizontal homogeneity of the flow over the probed volume. In the case of the Halo Streamline, no information about the horizontal wind can be derived from the measurements in the vertical staring mode, which only measures the vertical component of the wind speed. U is then retrieved from a sine-wave fitting from the VAD scans that are performed every 12 min".

Moreover, we have added and modified the following sentences in Section 4:

"It is reasonable to explain the higher error (~ +10%) of the Halo Streamline compared to the WINDCUBE lidars at 100m AGL as a consequence of the differences in the spatial dimensions that are samples by the two lidars. While the lidar beams of the WINDCUBE are tilted, and they therefore include turbulence contributions in the horizontal dimension (which is the only contribution considered in the determination of $\epsilon$ from the sonic anemometers), $\epsilon$ from the Halo Streamline is only retrieved using information from the vertically pointing beams. Moreover, the necessary approximations adopted in the determination of the horizontal velocity U for the Halo Streamline lidar, as explained in Section 3.2, likely determine an additional error increase for this lidar."

*References:*

- *Mann, J., 1994. The spatial structure of neutral atmospheric surface-layer turbulence. Journal of fluid mechanics, 273, pp.141-168.*
- *Kaimal, J.C., Wyngaard, J.C.J., Izumi, Y. and Coté, O.R., 1972. Spectral characteristics of surface-layer turbulence. Quarterly Journal of the Royal Meteorological Society, 98(417), pp.563-589.*

These results of appropriate time scales for reducing error are very interesting, but can they be applied everywhere? With the dependence on stability and scales of turbulence, terrain would undoubtedly have a large effect on the time scales with minimum error. If there are no sonics available for the error analysis done here, and individual spectra need to be inspected to find an appropriate inertial range, the method breaks down and isn't reasonable. This problem needs to be addressed here.

We have refined our approach to propose an alternative to use when measurements from co-located sonic anemometers are not available. We have included in the manuscript the following additional subsection:

### 4.1 Determination of the optimal time scales to retrieve $\epsilon$ from lidars in absence of co-located sonic anemometers

The availability of multiple sonic anemometers co-located with the lidars at XPIA has allowed for a direct comparison between $\epsilon$ estimates from different instruments to determine the optimal length scales, in different stability conditions, to use when retrieving $\epsilon$ from Doppler lidar measurements. This approach does not require the direct calculation of spectra from the line-of-sight velocity measured by the lidars, and therefore it represents a time-efficient technique. However, the proposed method is only viable when sonic anemometers are deployed in the near vicinity of a lidar, and when measures of atmospheric stability are available.

When a comparison with sonic anemometer data is not possible, the appropriate time scale to use in the lidar retrieval of $\epsilon$ can be determined by finding the maximum wavelength within the inertial sub-range in the velocity spectra from the lidar measurements. To do so, spectral models can be fitted to the observed spectra. Several models have been proposed for turbulence spectra in different stability conditions (Kaimal et al., 1972; Panofsky, 1978; Olesen et al., 1984). We test the spectral model proposed by Kristensen et al. (1989), which proposes expressions for both the cases of an isotropic and an anisotropic horizontally homogeneous flow. To validate our results and test this alternative approach to derive $\epsilon$ from lidar measurements, we use data from the Halo Streamline lidar to estimate the maximum wavelength $\lambda_z$ within the inertial subrange. Since the Halo mainly operated in a vertical stare mode during XPIA, we consider the following expression for the turbulence spectrum of the vertical component of the wind speed:

$$S(k) = \frac{\sigma_z^2 l_z}{2\pi} \frac{1 + \frac{8}{3}\left(\frac{l_z k}{a(\mu)}\right)^{2\mu}}{\left[1 + \left(\frac{l_z k}{a(\mu)}\right)^{2\mu}\right]^{5/(6\mu)+1}} \quad (16)$$

where $k$ is the wavenumber, $\sigma_z$ is the standard deviation of the vertical component of the wind speed used to compute the spectrum, $l_z$ is the integral scale of the vertical velocity along the horizontal flow trajectory, and the parameter $\mu$ controls the curvature of the spectrum. We use $\mu = 1.5$, which provides a good match with our experimental spectra, as also found in previous studies (Lothon et al., 2009; Tonttila et al., 2015). The parameter $a$ can be expressed as a function of $\mu$ as:

$$a(\mu) = \pi \frac{\mu \Gamma\left(\frac{5}{6\mu}\right)}{\Gamma\left(\frac{1}{2\mu}\right)\Gamma\left(\frac{1}{3\mu}\right)} \tag{17}$$

We calculate spectra using 10-min consecutive data, and we fit the spectral model to the experimental data, leaving out frequencies greater than $0.2$Hz, which are affected by instrumental noise (Frehlich, 2001), not modeled here. An example of a measured spectrum and the fit resulting from the model are shown in Figure 9. The transition wavelength $\lambda_z$ between the inertial sub-range and the outer scales can be expressed as a function of the integral scale $l_z$ and the parameter $\mu$:

$$\lambda_z = \left[\frac{5}{3}\sqrt{\mu^2 + \frac{6}{5}\mu + 1} - \left(\frac{5}{3}\mu + 1\right)\right]^{1/(2\mu)} \frac{2\pi}{a(\mu)} l_z \tag{18}$$

Following the approach in Tonttila et al. (2015), we estimate the timescale corresponding to this transition wavelength by dividing $\lambda_z$ by the collocated wind speed derived from the closest PPI scan performed by the Halo Streamline lidar.

To compare the results from this approach with what we obtain from the comparison with dissipation rates from the sonic anemometer data, we apply this technique to the data from the Halo Streamline for the whole period of XPIA, and calculate the average timescales for different stability conditions at $100$m AGL. We obtain an average time scale of $32$s in stable conditions, and $73$s in unstable conditions. Both these values compare well with what is found with the more time-efficient comparison with the sonic anemometer retrievals (values in Table 2), thus confirming that the use of spectral models can be considered a valid alternative for the determination of the optimal sample lenghts to retrieve $\epsilon$ from lidar data.

The use of spectral models to determine the appropriate sample size to use when retrieving $\epsilon$ from lidars can also be applied when information about atmospheric stability are not available or accurate. In these cases, instead of calculating an average optimal sample size for each stability condition, an appropriate time scale can be determined at each time $\epsilon$ is retrieved from lidar measurements, from a single spectrum. We compare $\epsilon$ values from the sonic anemometers and from the Halo Streamline lidar, with the optimal time scales obtained from both the proposed approaches (comparison with the sonic anemometer data and analysis of instantaneous spectra) in Figure 10, for the same time period shown in Figure 7. The use of spectral models to determine the extension of the inertial sub-range in the lidar spectra produces valid estimates of $\epsilon$: for this case we obtain a MAE$= 0.40$, and a correlation coefficient $R^2 = 0.78$.

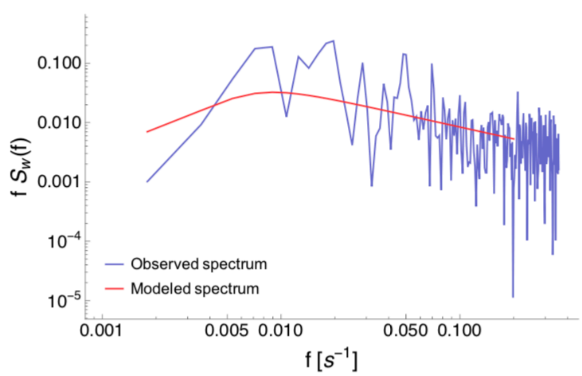


**Figure 9.** Example of power spectral density of the vertical component of the wind speed as measured by the Halo Streamline lidar on 11 March 2015 18:05 UTC. The red line represents the fit according to the spectral model from Eq. (16).

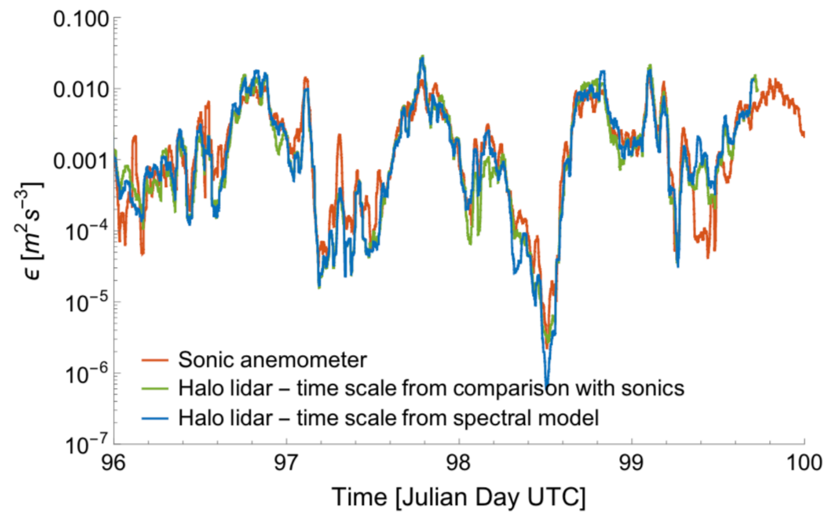


**Figure 10.** Time series from 6 April 2015 00 UTC to 10 April 2015 00 UTC comparing $\epsilon$ from sonic anemometers and the Halo Streamline lidars at 100m AGL, where the time scales for the lidars have been determined with both the proposed approaches (comparison with $\epsilon$ from sonic anemometers and fit with spectral models). Data have been smoothed with a 30-min running mean.

*References:*


- *Caughey, S.J. and Palmer, S.G., 1979. Some aspects of turbulence structure through the depth of the convective boundary layer. Quarterly Journal of the Royal Meteorological Society, 105(446), pp.811-827.*
- *Kaimal, J.C., Wyngaard, J.C.J., Izumi, Y. and Coté, O.R., 1972. Spectral characteristics of surface-layer turbulence. Quarterly Journal of the Royal Meteorological Society, 98(417), pp.563-589.*
- *Kristensen, L., Lenschow, D.H., Kirkegaard, P. and Courtney, M., 1989. The spectral velocity tensor for homogeneous boundary-layer turbulence. In Boundary Layer Studies and Applications (pp. 149-193). Springer, Dordrecht.*
- *Lothon, M., Lenschow, D.H. and Mayor, S.D., 2009. Doppler lidar measurements of vertical velocity spectra in the convective planetary boundary layer. Boundary-layer meteorology, 132(2), pp.205-226.*
- *Olesen, H.R., Larsen, S.E. and Højstrup, J., 1984. Modelling velocity spectra in the lower part of the planetary boundary layer. Boundary-Layer Meteorology, 29(3), pp.285-312.*
- *Panofsky, H.A., 1978. Matching in the convective planetary boundary layer. Journal of the Atmospheric Sciences, 35(2), pp.272-276.*
- *Tonttila, J., O'Connor, E.J., Hellsten, A., Hirsikko, A., O'Dowd, C., Järvinen, H. and Räisänen, P., 2015. Turbulent structure and scaling of the inertial subrange in a stratocumulus-topped boundary layer observed by a Doppler lidar. Atmospheric chemistry and physics, 15(10), pp.5873-5885.*

- page 2, line 5: Is the 3km scale a result from Albertson et al also? If so, move citation to end of sentence. If not, include citation for this fact also

We have eliminated the explicit reference to the 3km scale, and limited the sentence after "coarse scale". We have also added two references (Lundquist et al. 2007, Mirocha et al. 2010) at the end of the sentence.

*References:*

- *Lundquist, J.K. and Chan, S.T., 2007. Consequences of urban stability conditions for computational fluid dynamics simulations of urban dispersion. Journal of applied meteorology and climatology, 46(7), pp.1080-1097.*
- *Mirocha, J.D., Lundquist, J.K. and Kosović, B., 2010. Implementation of a nonlinear subfilter turbulence stress model for large-eddy simulation in the Advanced Research WRF model. Monthly Weather Review, 138(11), pp.4212-4228.*

- page 5, table 1: include the temporal resolution of each lidar

The temporal resolution of the lidars (~ 1 Hz) has been added to the table.

- page 7, lines 14-15: what is theta here? How small is small?

A specification about the value of theta "(< 0.1 mrad)" has been added to the sentence.

- page 7: Are LOS velocity spectra calculated for all beams or only the vertically pointing? If all, isotropy must be assumed. Clarify and comment on this.

We have included the following sentences to clarify this point:

"For the WINDCUBE lidars, the variance of the observed line-of-sight velocity $\sigma_v^2$ can be calculated as average from all the beams. In doing so, we include turbulence contributions from both the horizontal and vertical dimensions, and we make the limiting (Kaimal et al. 1972, Mann 1994) assumption of isotropic turbulence. For the Halo Streamline lidar, which operated in a vertical stare mode, $\sigma_v^2$ is calculated from the vertically pointing beam, and therefore $\epsilon$ will strictly include turbulence contributions only in the vertical dimension, thus possibly determining different values compared to what is retrieved from the WINDCUBE lidars."

*References:*

- *Mann, J., 1994. The spatial structure of neutral atmospheric surface-layer turbulence. Journal of fluid mechanics, 273, pp.141-168.*
- *Kaimal, J.C., Wyngaard, J.C.J., Izumi, Y. and Coté, O.R., 1972. Spectral characteristics of surface-layer turbulence. Quarterly Journal of the Royal Meteorological Society, 98(417), pp.563-589.*

- page 10, lines 4-5: why is a wider inertial range expected at higher altitudes?

We have explicitly explained that this would be due to an increase in the integral scale of turbulence with height, and we have added a reference: "different altitudes can also impact the extension of the inertial sub-range, with a wider development expected at higher heights, as the integral length scale of turbulence increases (Wang et al. 2016)".
*Reference: Wang, H., Barthelmie, R.J., Doubrawa, P. and Pryor, S.C., 2016. Errors in radial velocity variance from Doppler wind lidar. Atmospheric Measurement Techniques, 9(8), p.4123.*

- page 14, line 15: this final sentence doesn't make sense. Why would the filter change the choice of shorter time scales being averaged?

We agree that the sentence can be confusing, therefore we have eliminated it.

**Technical Corrections:**

We thank the reviewer for all the suggested technical corrections, which have been incorporated in the revised version of the manuscript and supplement.

- On all figures with units of epsilon shown, use $m^2$ $s^{-3}$, not $m^2/s^3$

The plot labels have been corrected.

- When referring to figure subplots, remove space between number and letter (check AMT standard)

The space has been removed.

- Include the time scale of epsilon on all plots

The captions of figures now include the time scale of epsilon.

- Yellow lines are hard to see, especially the yellow shading. I appreciate the use of consistent colors for each instrument across all figures, but need a better choice for yellow. If v1s are used rarely, use purple or green instead of yellow, maybe the same color with different weights or dashes?

We have used green for the Halo Streamline throughout the manuscript. Yellow is not used for the WINDCUBE v1-68, which appears in a limited (2) number of figures in the main manuscript. In the supplement, yellow is now not used at all.

All the following corrections have been applied.

Page 1

- line 7: accurate forecast

Page 2

- 1: small enough that molecular diffusion is capable of dissipating
- 7: when using models
- 34: velocity spectra. We assess the uncertainty of this method, and present

Page 3

- 5-6: as a case study... during a nocturnal low-level jet event

- 18: measurement accuracy or precision (not resolution)
Page 4
- 14-15: For atmospheric stability, we classify neutral conditions as L ... unstable conditions as ... stable conditions as...
- 24: who deployed the v2? The revised sentence now includes "was deployed by the University of Colorado Boulder"
- 30: wrong dates for the v1s
Page 5
- 19: remove space after tower
Page 6
- 5: which must be within
Page 7
- 9: define k1 and N earlier
Page 8
- 6: period after equation
- 22-23: different heights and atmospheric conditions
Page 9
- 11: looks more like 40s, not 50s
Page 10
- 24: found to be at shorter time scales than unstable
Page 11
- 9-10: because they occurred less than 5% of the time
Page 12
- 9: due to hard strikes
- 10: v1-61, so the comparison... 150m AGL has been performed using only this lidar's data...
Page 14
- 8 conditions and smoothing
- 12: note the time scales of the raw time series We have added this specification: "(one value every ~ 4 s)".
- 20: lower case section (only capitalize when referring to Section X)
- 23: Materials, and are
- 26 & 27: space before units
- 28: intermittent
Page 16
- 1: lowercase section
- 2: confusing wording
- 14: not all instruments
Page 17
- 1-2: $L>0$ and $L<0$
Page 18

- 4: impact on
- 11: increases of 1-2 orders (stable increases two orders)

Page 19

- 1: wind energy resources
- 18: cite Yang et al, (2017). Sensitivity of turbine-height wind speeds to parameters in planetary boundary-layer and surface-layer schemes in the weather research and forecasting model. *Boundary-Layer Meteorology*, *162*(1), 117-142.

Figure 1: legend on right plot is not readable – match size of left legend. Colors on right subplot does not correspond to color scale legend on left subplot – include a new color scale for this subplot also.

The font size used in the right panel has been increased, and a new color scale has been included.

Table 1: WINDCUBE v1 (61 & 68)

Corrected.

Figure 5: Use a different color than yellow (purple?)

Purple is now used.

Figure 6: variability (misspelled); indicate which time scale is used for each stability class: minimum MAE for optimized Nt, at the appropriate time scales?

The caption has been modified accordingly.

Figure 8: labels columns (raw and smoothed) and rows (all stability, stable, unstable) on figure

Labels have been added.

Figure 9: label instruments on figures; nighttime variability mentioned in text is hard to see on this color scale – maybe change to "jet" blue-red scale; I'd prefer the y-axes to be the same on the two left plots, or at least both start at 0; are these 30-minute or raw values?

We have labeled the instruments on the plots. Thank you for your suggestion about the color scale. However, we have decided to keep the current color scale, as 'jet' can create some confusion, especially when printed in black and white, as shown in Light and Bartlein 2004 and Stauffer et al. 2015.

We have now used a common vertical axis for all the panels as suggested.

Raw values are used, and this is now specified in the caption of the Figure ("Daily climatology of turbulence dissipation rate derived from raw values …").

*References:*


- *Light, A. and Bartlein, P.J., 2004. The end of the rainbow? Color schemes for improved data graphics. Eos, Transactions American Geophysical Union, 85(40), pp.385-391.*
- *Stauffer, R., Mayr, G.J., Dabernig, M. and Zeileis, A., 2015. Somewhere over the rainbow: How to make effective use of colors in meteorological visualizations. Bulletin of the American Meteorological Society, 96(2), pp.203-216.*