Response to Anonymous Referee 2

Referee comments are indicated in *italic*, followed by our reply.

SYNOPSIS:
The paper describes a new method for estimating the height of the mixed layer at levels below the typical minimum range of a vertically looking Doppler lidar.

GENERAL COMMENTS:
The topic is both timely and relevant, and the manuscript is very well written. There appears to be some room for improvement in the theoretical discussion of the method, while the data sets presented are sufficiently illustrative and well analyzed.

We would like to thank the referee for his insightful comments, which have improved the quality of the manuscript.

SPECIFIC COMMENTS:
- My major complaint is the lacking theoretical justification of the method: Equation (1) comes out of nowhere and is not justified at all. The decomposition of the wind field can be done in various ways, but it is not clear what approach the authors had in mind. It appears to be a mix of the classical Reynolds decomposition applied in statistical turbulence theory (homogeneous or mean term and turbulent term) and a Taylor power series expansion terminated after the linear part (deformation, divergence, but then the rotational term is missing). The additional term due to "surface interactions" appears to be somewhat contrived since it would not fit in either decomposition approach. Furthermore, the notation is non-standard and probably more confusing than helpful. I would suggest that the authors revise section 2.2 to achieve the required clarity and correctness. In view of the further development in eqns. (2-10), a simplification seems to be possible since the authors argue that the deformation term, the divergence term and the "surface term" are more or less negligible in the situations considered.

We have reformulated our build-up towards the VAD-based proxy for mixing so that we begin with a formula analogous to Reynolds formulation. It is quite true that neither Reynolds nor Taylor decomposition consider the surface effects on wind field. However, close to surface, where the focus of this paper is, surface interactions cannot be neglected – in fact, they are the reason why we cannot use Eq. 2 directly to calculate mixing. We have emphasized this in the revised text. However, we would like to keep the assumptions made clearly visible for the reader and thus we did not simplify the equations for deformation, divergence and surface interactions.

We have re-written the section 2.2 from line 2 on page 12225 to line 22 on page 12226 as follows:

"Considering one radial measurement in a VAD, the observed radial velocity (V_R) at a single range gate can expressed analogous to the Reynolds formulation in statistical turbulence theory:

$$V_R = V_{wind} + R, \qquad (1)$$

where V_{wind} is the radial component of homogeneous horizontal wind and R is the deviation from the homogenous horizontal wind. The horizontal wind component V_{wind} is then derived by fitting a sinusoidal curve to V_R as a function of the azimuthal angle (Fig. 2a) for each elevation level in a VAD, with R being the residuals of these fits.

Contrary to the Reynolds formulation, though, in a VAD the deviation term R contains more components than the purely turbulent fluctuations. These additional components arise from fact that, over the relatively large volume of atmosphere covered by the VAD scan, there are often non-turbulent changes in the horizontal wind speed and direction on scales of hundreds of metres to kilometres that are also contained in R in Eq. (1) when V_{wind} is estimated from a fit over the full VAD. Some of these contributions (e.g. divergence, relative vorticity, stretching and shearing deformation) are estimated through Taylor expansion (Browning and Wexler, 1968).

Within the first hundred metres above the surface, the focus of this study, R can also contain significant contributions from local distortions. Typical surface-induced changes would be wind flows around a building or wind channelling around an island. With these considerations, we express R as

$$R = V_{turb} + \sum_{i=1}^{\infty} V_i + V_{local} + \delta \,, \qquad (2)$$

where V_{turb} is the contribution from turbulent mixing that we are interested in, V_i represent the harmonic terms from the Taylor expansion, V_{local} is the deviation due to local effects, and δ is the instrumental measurement uncertainty.

In order to extract the atmospheric turbulent mixing information from this residual, the non-turbulent contributions have to be obtained or estimated. In quiescent conditions, the terms V_i, and V_{local} in (2) may form most of the residual. This is evident when correlating the residuals of two consecutive range gates as in Fig. 2b; a high correlation indicates that the residuals are dominated by flow patterns with length scales that are large compared to the 30 m radial resolution of the instrument.

In most environments, however, quantifying V_{local} with reasonable accuracy would require such detailed knowledge of the surface at the measurement location that it makes it impractical to determine V_{turb} directly from Eq. (2). Therefore, we consider the change in V_R from one range gate at distance r to the next range gate at (r + 30 m) for one radial measurement:

$$V_R(r) - V_R(r + 30m) = \Delta V_R = \Delta V_{wind} + \Delta R \,. \qquad (3)$$

In this way, the problem of determining the non-turbulent changes in the wind field within the VAD volume has been reduced to the question of whether these changes are significant on the scale of the range resolution of the Doppler lidar. The term ΔR in (3) can be expanded to

$$\Delta R = \Delta V_{turb} + \sum_{i=1}^{\infty} \Delta V_i + \Delta V_{local} + \upsilon \,, \qquad (4)$$

where

$$\upsilon = \sqrt{\delta^2(r) + \delta^2(r + 30m)} \,, \qquad (5)$$

i.e. we have assumed that the instrumental measurement uncertainty for the two range gates is uncorrelated. The changes in the wind field that the Taylor expansion represents are assumed to occur over length scales that are significantly larger than the Doppler lidar range resolution of 30 m (e.g. Browning and Wexler, 1968) and therefore we state here:

$$V_i(r) \approx V_i(r+30m); \Delta V_i \approx 0 \qquad (6)$$

for all *i*, Similarly, if the localized effects in the wind field can be considered smooth at the Doppler lidar range resolution scale (here 30 m), i.e. the surface is reasonably homogeneous or the measurement is not close to the surface, then we assume

$$V_{local}(r) \approx V_{local}(r+30m); \Delta V_{local} \approx 0\,. \qquad (7)”$$

- Section 2.2, page 7, line 21: The statement that the instrument uncertainty with regard to velocity is only a function of the signal-to-noise ratio seems to be a simplifying assumption. Other dependencies might also exist, like a bias or scanner pointing inaccuracies. Furthermore, while precipitation increases the SNR this may not necessarily improve the accuracy of the wind estimation since there can be a discrepancy between the wind velocity and the velocity of the particles. This is particularly relevant for the determination of the vertical wind component.

We have modified lines 11-16 on page 12227 address these very good points raised by the referee: “The instrument uncertainty in velocity δ is primarily a function of the signal-to-noise ratio, SNR, (Pearson et al., 2009) and is calculated for every individual radial velocity measurement in a VAD. Based on pointing accuracy tests performed during both campaigns towards hard targets at known direction and distance we consider the pointing accuracy error negligible, especially when compared to the uncertainty arising from the measurement itself.

The choice of median in (10) is to avoid outliers skewing the distribution. In general, most of the points in a particular VAD display similar sensitivity, but the presence of cloud or precipitation can increase SNR, whereas certain radials may be completely or partially obscured by buildings or trees. Measurements in the presence of precipitation have to be carefully evaluated as the signal can be dominated by the terminal fall velocity of the drop, and large drops do not necessarily track the turbulent motion of the air.”

- Section 2.2., page 8, line 1: It is not clear how the threshold of 1.58 m^2/s^2 is obtained from an estimated σ^2VAD for a SNR > 0.0025. Should this not be a function of the elevation angle used in the VAD-scan?

We have rewritten the lines 17-18 on page 12227 to clarify this issue:
“. In terms of σ^2_υ the SNR limit of 0.0025 is equivalent to a threshold of 1.58 $m^2\ s^{-2}$ using the instrument specifications given in Table 1. This is derived by calculating δ from SNR according to O’Connor et al., (2010), and then applying Eq. 10. Note that this assumes that the turbulence is isotropic in nature.”

- Section 3.1., page 9, lines 3-6: Based on Fig. 3 it is stated that the relationship between σ^2_{VAD} and σ^2_w is reasonably linear, but especially the data from Loviisa do not strongly support this claim. It is also not very obvious that Fig. 3 supports the argument that the relationship between σ^2_{VAD} and σ^2_w is independent of the VAD elevation angle. Given the importance of these assertions, the authors should discuss any possible limitation of their conclusion.

The comparison in Loviisa is poorer than the comparison at Limassol, which we think is largely due to 2 factors at Loviisa: narrow range of variability in observed values (i.e. little variation in the turbulent properties since there is minimal diurnal influence in Finland in winter); and lower sensitivity because of low aerosol loading meaning fewer data points and longer integration time (i.e. slower scanning and thus longer delay between different scans). We have added some more discussion on this point in Sect. 3.1.

- *References: The authors should use standard abbreviations for Meteorologische Zeitschrift, Boundary-Layer Meteorology, Quarterly Journal of the Royal Meteorological Society and Journal of Geophysical Research.*

These references have been corrected.

- *Table 1: A lens diameter should not have the dimension of μrad.*

The divergence of the lens is 33 μrad and lens diameter is 8 cm.
These have been corrected in the Table 1.