Reply to comments from referee #3

R. Rüfenacht, A. Murk, N. Kämpfer, P. Eriksson, S. A. Buehler

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- blue: referee's comments
- green: author's replies

General Comment:

This paper describes updates on the wind measurement at upper stratosphere and lower mesosphere, using the improved radiometer WIRA. The authors implemented a new instrumentation of a single-side band receiver, and also introduced a new retrieval processing using the ARTS package. Comparisons with the ECMWF model are presented in order to validate the output. The content of the paper well fits with the scope of the AMT journal, and indeed the Doppler measurement of upper atmospheric wind field is scientifically highly important. Before recommending to the publication, however, I would like to ask the authors to consider following comments. My main concern is: the lack of one reference paper which covers the same observation targets with a similar technique, and insufficient description, at least in my eyes, on the quantitative error analyses.

A more detailed error analysis has been performed. The studied influences were: uncertainties in the spectral parameters of line center frequency, line intensity and the pressure broadening parameters, influence of differences in the ozone profile on the wind retrieval, influences of the assumed temperature profile and influences of baseline ripples and frequency dependent calibration errors. It appeared that the temporally and locally constant temperature profile used in the retrieval could lead to larger inaccuracies than we had expected. Therefore the entire data series was re-computed with the daily temperature profiles from MLS on AURA. For this re-computation a baseline correction was performed before the retrieval where possible (for the time where the broadband spectrometer with 1.5 GHz bandwidth was running, i.e. the measurement campaigns at OHP and Maïdo). Moreover we set the maximum altitude resolution for a measurement to be regarded as trustable to 20 km for all the analyses presented in the paper. In practice a resolution lower than 20 km is reached on very rare occasions only. The upper limit of the trustable altitude range is usually determined by the condition that the altitude accuracy needs to be better than 4 km.

Specific comments:

There is one paper from satellite-based wind measurements using a submm radiometer (Baron et al., 2013). Please consider including this study as one of the references of previous studies. Note that Baron et al. also compared the difference between the observed wind and ECMWF model (which also indicated somehow large discrepancy of the measurement from ECMWF at the mesosphere compared to the stratosphere), and discussed the wind field modulation due to SSW (but of the different year); which I do believe a good and important reference for the authors' study.
Thank you for pointing this out. We know about this experiment but the reference somehow got forgotten at the time of writing. We do agree that this is an important reference and added it in the introduction.

...And this is just a suggestion as a possible future work: the data from the prototype WIRA with double-side band can be used for the horizontal wind (as the authors describe in the first paragraph of Sect.5). Then, it would be interesting to compare those prototype WIRA measurements in early 2010 with the SMILES wind product particularly at the mesosphere where ECMWF shows the discrepancies.
Unfortunately the operation of SMILES stopped on 21 April 2010 due to a local oscillator failure. WIRA had not taken any atmospheric measurements by this time.

p. 7722, L 10 – 13. "However, this information can be neglected in case of retrieving volume mixing profiles....(e.g., Verdes et al. 2005)."
I think whether this is negligible or not is just a matter of degree: mean, if the measurement data are with very good signal-to-noise ratio and/or if one needs very precise and accurate trace gas retrieval, then the uncertainty of the line position can also be a serious error source, I think. Moreover, I don't see the point of putting this sentence here in this paragraph where the authors describe about the radiative transfer principle. I guess the effect of $\Delta\nu(s')$ is automatically included in the radiative transfer computation of the O3 retrieval since the authors retrieve wind and O3 simultaneously. If so, I would suggest remove this sentence.
This statement has been removed as indeed we do not neglect $\Delta\nu(s')$ in any of WIRA's retrievals.

p. 7723, L 25. "do not directly influence the wind retrieval".
I do not understand the meaning of the word "directly" here. What can be the indirect influence? Please consider making the sentence clear.
This and the previous sentence have been adapted: "In practice a major advantage of this behaviour is that calibration errors do not influence the wind retrieval as long as they can be regarded as frequency independent. In our narrow band measurement situation this can be assumed as true and calibration errors be thought of as causing an offset or stretching of the spectrum in the intensity dimension."

p. 7724. L 4 – 12. "For the ozone retrieval the values of K ... profile retrievals."

The last words "for species profile retrievals" are not clear. I think this paragraph describes a typical change of the observed spectrum brightness temperature, ΔT_B, with respect to the variation of wind or O_3 profile. And, I think it is non-trivial to regard such ΔT_B being equal to the retrieval sensitivity, as retrieval requires the information of $\mathbf{S_a}$. Thus I do not understand why the authors can mention about "species profile retrieval" here. Also, the amplitude of ΔT_B at one frequency alone is not enough to discuss the measurement sensitivity to physical parameters. I think ΔT_B integrated over the frequency and also gradient of ΔT_B in the frequency domain are also important factors when judging the measurement sensitivity... Perhaps my interpretation of this sentence is not correct, but please make it clear what the authors want to say here, and consider the improvement of statement.
This formulation was indeed misleading, we just wanted to discuss effects of typical ozone and wind variations on atmospheric emission spectra here. The sentence has been modified to: "Therefore we can state that the effect of wind variations on the measured brightness temperature spectra is approximatively thirty times smaller than the effect of typical ozone variations."

Related to this statement: Please clarify the impact of error on O_3 profile retrieval on the wind retrieval. If the authors wanted to describe this with the above commented text, I would suggest the re-arrange the manuscript (as I commented above I am not sure whether ΔT_B can be used for this purpose), and I would move this discussion into the error analysis part. The way how to describe such an error is up to the authors, but one possibility may be to evaluate following quantities:

$$\frac{\partial \hat{\mathbf{x}}_{\mathbf{los\_wind}}}{\partial \mathbf{x}_{\mathbf{O_3}}} \qquad (1)$$

in the averaging kernel matrix.
The part of the averaging kernel matrix describing the dependence of the retrieved wind from the retrieved ozone profile is appended to this document in figure 2. An estimate of the wind originating from the difference in the ozone profiles between west (north) and east (south) for zonal (meridional) wind can be found by multiplying this part of $\mathbf{A}$ with the difference in the ozone profiles. Therefrom we conclude that the error is smaller than 1 m/s when assuming the difference in ozone between the two observation directions used for the wind determination to be 5% as shown in figure 3 appended to this document.
Moreover, atmospheric ozone profiles which are far away from the a priori profile assumed in the retrieval might be compensated by other variables. Therefore, the response to ozone variations has also been simulated in our Monte Carlo error simulation. The results for a sample day are shown in figure 4 appended to this document. The influence of ozone variations on the wind retrieval is described in the reviewed manuscript in the new subsection about bias errors in the "Error analysis" section (Sect. 4.3). The excerpt of this subsection can be found in the appendix to the present document.

p. 7725. Sect. 4 WIRA's retrieval setup
I think that the ARTS model can handle inhomogeneous spherical shells of the atmosphere (i.e. capable of retrieving 3-D structures). Do the authors assume homogeneous spherical shell for the atmospheric modelling (maybe yes since

the difference between east and west or north and south directions is computed afterwards)? And, it would be helpful for readers if the authors add some more description about the detailed configuration on ARTS, such as what kind of continua absorption models are used, etc.

Our setup assumes there are no horizontal variations in the atmosphere, just vertical ones. That is, the atmosphere consists of "homogeneous shells".

The continua absorption models are now mentioned in the manuscript: "WIRA's retrieval is a combined retrieval which simultaneously determines wind, ozone, (continuum) water vapour (according to Rosenkranz (1993)) and a second order polynomial for basic corrections of baseline issues. The oxygen continuum according to Rosenkranz (1998) and the nitrogen self broadening according to Liebe et al. (1993) are included in the model but are not retrieved."

p. 7726. L. 2, 8 "altitude accuracy"

I completely agree with the authors considerations for the trustable vertical range of the retrieval. However, the word accuracy sounds like the absolute correctness of the altitude (pressure) of the retrieved wind profile. Such a correctness cannot be discussed from averaging kernel since they provide only "relative" correctness of the altitude within the forward model. Is there any idea for re-wording?

After reflection "accuracy" is still the most appropriate term. "Uncertainty" would probably lead some readers to assume that we do not exactly know about the altitude but that it is correct on average. This would be a misinterpretation. Our retrieval runs on pressure coordinates and depending on the assumptions used for transformations to altitude in kilometers, the altitude might be slightly uncertain. Therefore if indications of altitude in kilometers are given in the manuscript, they are always referred to as "approximative altitudes".

p. 7728. Sect 4.3 Error analysis

This is my major concern. If I read the manuscript correctly, in this section the authors discuss the retrieval error from the measurement noise (random noise) which characterizes the "precision" of the wind retrieval. I strongly expect that the authors add further investigation about "accuracy" (bias uncertainties) of the retrieval as many other remote sensing observation publications do. Such systematic-error analysis could help us to understand possible reasons of having differences between ECMWF or other data set. Perhaps the impact of random noises would be so large that most of bias uncertainty can be negligible. Even in such a case, please confirm it in the manuscript.

A more extended error analysis has been performed. A new subsection about bias uncertainties has been added to Sect. 4.3. An excerpt of this new part of the manuscript can be found in the appendix to the present document. The effects of the following spectral parameters have been studied: line intensity parameter, line center frequency, pressure broadening coefficient, pressure broadening temperature dependency coefficient. Moreover the influence of the temperature profile assumed by the retrieval and the influence of ozone profiles strongly differing from the a priori assumptions or the effect of differences in the ozone profiles under different azimuths have been studied. Finally, also the effect of possible instrumental baselines and frequency dependent calibration errors have been investigated.

p. 7728. L 20 – 21 "As mentioned before the influence of calibration inaccuracies can be neglected for the wind retrieval..."
Do the authors consider only frequency *independent* calibration inaccuracies, such as a constant offset over all the frequency, here? If so, how about the frequency dependent calibration inaccuracy?
We indeed did not explicitly specify that we assumed calibration errors to be frequency independent. The sentence has been moved to the new paragraph about bias uncertainties by writing "frequency independent calibration inaccuracies" instead of just "calibration inaccuracies". In this paragraph also the influence of frequency dependent calibration inaccuracies is assessed.

p. 7729. L. 10 – 15. "It is dependent on the noise level... on the receiver type..."
It is not clear why the choice of single or double-side band receivers change the retrieval error. Is it just a matter of definition of noise temperature with respect to receiver type (signal-to-noise ratio of O_3 line should change between single or double side band, under the fixed noise level)? And, I am confused why the authors put the *same* noise level for single and double-side band system in order to represent typical clear and cloudy cases. Please add some more explanations why the retrieval error depends on the receiver type.
We agree that this statement might be unclear. Indeed the way receiver noise temperature is defined a single sideband (SSB) receiver with the same receiver noise temperature as a double sideband (DSB) receiver has a twice as high signal to noise ratio of the ozone emission line compared to a double sideband receiver. The reason is that the latter one builds the average between the signal (with the ozone line) and image (with a nearly frequency independent signal of comparable level) sideband as long as a sideband ratio close to 1 can be assumed. To clarify the situation the sentence 'It is dependent on the noise level of the input spectrum and on the receiver type (single or double sideband)" was modified to "It is dependent on the signal to noise ratio of the input spectrum which depends on the version of the receiver used to measure the emission line."
As the upgrade described in the paper "reduced the noise temperature from 880K double sideband to 740K single sideband" (p. 7720 l.29), the typical noise levels on the calibrated spectra measured with the single and the double sideband receiver versions are similar (when measuring 4 directions plus calibration targets with the SSB and 2 directions plus calibration targets), although this corresponds to a twice as good signal to noise ratio. For this reason the same noise levels for DSB and SSB have been chosen in the present simulation. To make this more clear the following statement has been added on page 7729, line 8: "By coincidence, due to the definition of single and double sideband noise temperature, the typical noise levels of spectra measured with the new single sideband receiver with less integration time at the respective sky positions (zonal and meridional wind measured in contrast to only zonal wind with the old receiver) are similar to the ones of spectra measured with the double sideband receiver before the upgrade described in Sect. 2."

p. 7729. L 13 – 15. "...the error ranges from 17 to 27 m s-1 ..."
I would like to know if these error values (standard deviation of the retrieved profiles using Monte Carlo method) agree with the retrieval error (measurement error and smoothing error), which defined in Rodgers OEM, computed from the

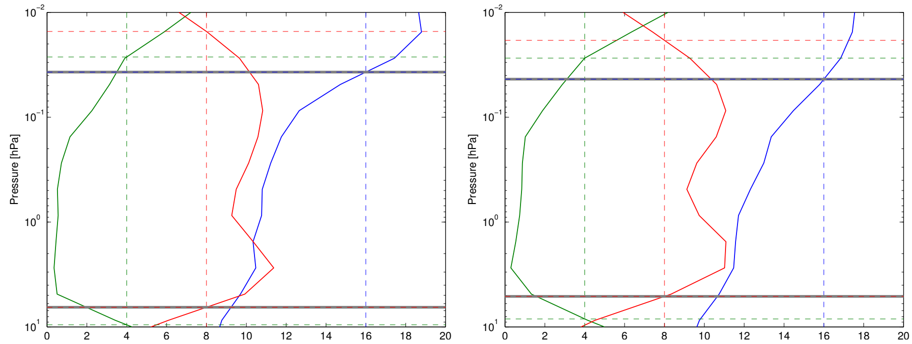
assumed measurement noise level.
As stated in the manuscript the smoothing and measurement errors definition by Rodgers rely on the a priori covariance matrices. However, for the reasons stated in Sect. 4.1 the a priori variance for the wind has been chosen larger than the variance which one obtains when building the variance over a time series of data of for example one/several years. Therefore also the diagnostic quantities of the error estimation by Rodgers are larger.
The smoothing error describes how large the uncertainty of the wind value at a specific altitude is because of the limited altitude resolution of a microwave radiometer by taking the indicated a priori covariance as a measure for the uncertainty in the wind field. The indication of the smoothing error can be omitted as long as the wind profiles to which the retrieved wind profiles are compared to are convoluted with the averaging kernels of WIRA (this is the case for the comparisons shown in the present paper, see cyan line in Figs. 14 and 15).
The error values specified here are the standard deviation of the retrieved profiles (of a set of at least 30 retrievals). This is a direct way to estimate the equivalent of the measurement error specified by Rodgers, without having to rely on the a priori covariance. When using the formula given by Rodgers with the too unnaturally large wind variances used in our retrieval one would obtain errors which are approximately 1.6 times larger than the ones obtained with the Monte Carlo method.
N.b.: We use the term observation error in the manuscript. Measurement error and observation error denote the same quantity.

p. 7732. Sect. 5.2 Comparison with ECMWF data
In the discussion about the difference between WIRA-measured wind and the ECMWF model output, do the authors take the accuracy of ECMWF into account?
Unfortunately, despite an extended search we could not find any indications of accuracy for the middle-atmospheric wind in ECMWF.

p. 7732. L. 26 – 27. "The authors do not see any reason why WIRA's zonal wind measurements should suffer from a systematical error in the mesosphere..."
I believe that this sentence has a convincing meaning only if the authors put quantitative descriptions about the systematic-error analysis. Please consider improving the manuscript.
The error analysis has been extended. Please see the reply to your comment to Sect. 4.3.

Figures Please try to improve the visibility of the plots: in some figures, it is difficult to read the numbers and labels of axis (particularly the superscripts of the pressure values).
Often the problem was to fit the figures with all subfigures onto one page in the discussion paper format as it is a requirement of AMTD. These figures shall be larger in the version published in AMT and thus also the readability of the axes labels. The visibilty of the plots will be re-checked once the manuscript is typeset in the AMT format.

Figure 9 I would change the position of the legend-box which is overlaying



(a) New single sideband receiver.

(b) Old double sideband receiver.

Figure 1: Version of figure 9 in the AMTD manuscript without legend to see all points of the plotted data.

on the plotted profile.

The problem is that the legend box in this figure is overlaying some plot data at every imaginable position. We believe the actual position is the least disturbing choice as the reader will (rightly, see attached figure 1) assume a rather linear interpolation of the hidden data.

Figure 11 Plotting the error profiles at both upper and lower-outside of the dashed line (trustable altitude range) as "wind observation error" is misleading. I would limit the y-axis range only at trustable vertical range.

The figure has been modified in this sense.

Figure 16 x-axis label "Relative offset... → I would write as "Relative difference.

The figure has been adapted in this sense.

References J. Quant. Spectrosc. Ra. → Is this an appropriate abbreviation in AMT? Please check.

Another abbreviation for this journal could be "J. Quant. Spectrosc. Radiat. Transfer". However, for AMT the titles should be abbreviated according to the ISI Journal Title Abbreviations Index. This index states "J. Quant. Spectrosc. Ra." is the abbreviation to be used.

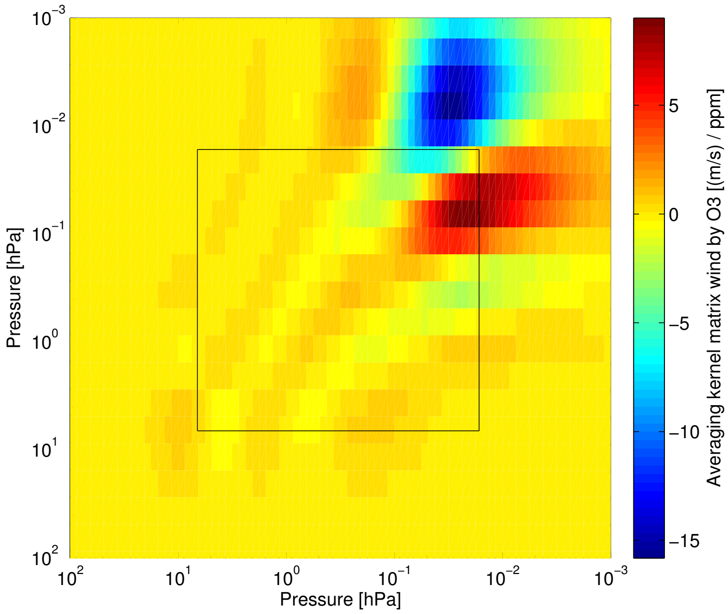


Figure 2: Example of the part of the averaging kernel matrix showing the dependence of the retrieved wind from the ozone profile for one single viewing direction (observation in westward azimuth on 23 Nov 2012). The black rectangle denotes the trustable altitude range of the retrieval.

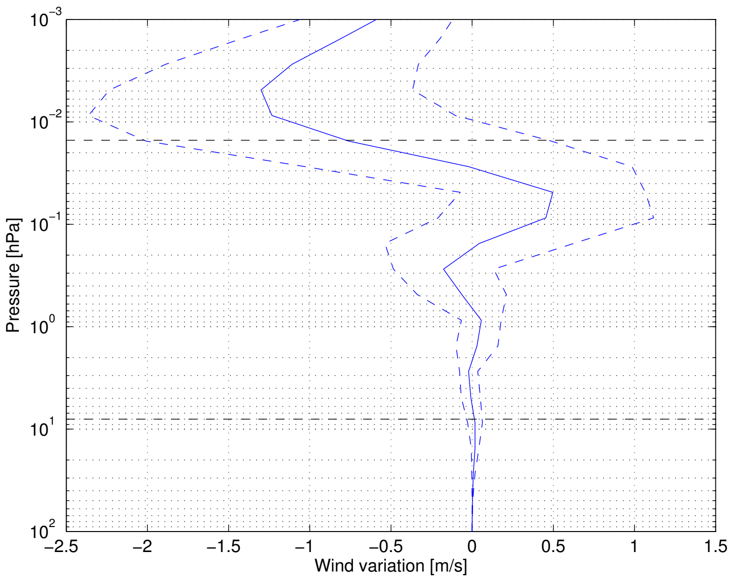


Figure 3: Influence of an ozone difference between east and west on the measured zonal wind. Mean and standard deviation for results calculated with 30 different averaging kernel matrices. The horizontal dashed lines delimit the trustable altitude range.

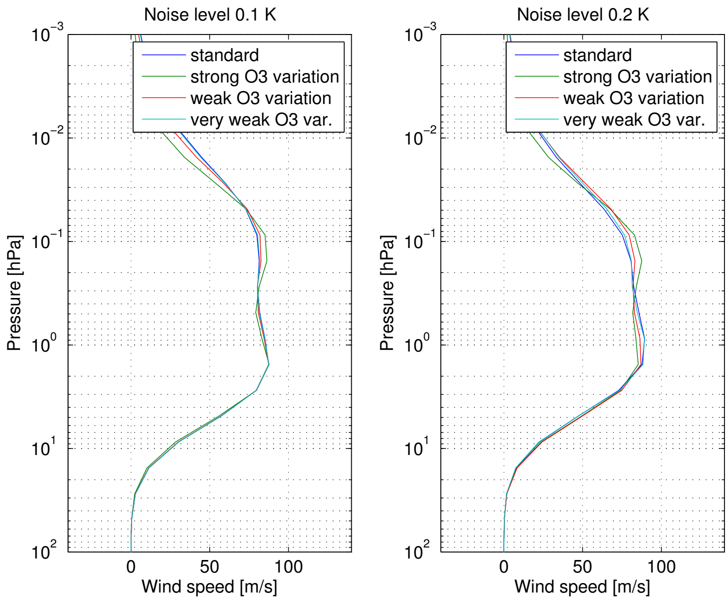


Figure 4: Retrieved wind profile with disturbed forward model ozone profiles: standard (ozone profile not disturbed), strong (ozone reduced by 30%, oscillation amplitude 10% of total ozone at the respective altitude), weak (ozone reduced by 10%, oscillation amplitude 5%), very weak (ozone reduced by 1%, oscillation amplitude 0.5%)

A Evaluation of possible sources for bias errors

In addition to the random error analysis also possible sources of biases in the retrieved wind have been extensively studied based on Monte Carlo simulations. The influence of errors related to uncertainties in the forward model parameters are displayed in Fig. 11. For these simulations the following quantities were perturbed: The centre frequency of the emission line according to the uncertainty indicated in the used spectroscopy catalog (Pickett et al., 1998), the line intensity by ±10%, the pressure broadening coefficient by ±10%, the temperature dependency coefficient of the pressure broadening by ±10% and the temperature profile by ±3%. It appears that none of these parameters can cause a significant bias in the retrieved wind.

Another possible source of biases could be an instrumental baseline. The spectra from WIRA contain a baseline which is dominated by a standing wave originating from reflections at the ambient temperature calibration target and the horn antenna. This oscillation can be assessed when using data from the broadband spectrometer and is corrected in the routine data processing where possible (the broadband spectrometer board was not running before September 2012, since then the baseline correction succeeds in more than 90% of the cases). The amplitude of the baseline was found to be 0.16 K on average on the spectra measured with the single sideband receiver and is expected to be significantly smaller for the double sideband measurements because of the phase mismatch of the baseline in the signal and image sideband. The influence of baselines with 0.16 K amplitude and a period corresponding to the standing wave between the calibration target and the antenna has been simulated for different phase shifts. The results in Fig. 12 illustrate that the baseline of WIRA is uncritical for the wind measurements in any situation.

As mentioned in Sect. 3 the influence of frequency independent calibration inaccuracies can be neglected for the wind retrieval due to the antisymmetric behaviour of the rows of the Jacobian. Frequency dependent calibration inaccuracies are expected to be very small in our narrow band application. However, the results in Fig. 12 show that even such inaccuracies would not significantly bias the wind measurements as their effect on the measured spectra would be similar as the one of a baseline.

Atmospheric ozone profiles which are far away from the a priori profile assumed in the retrieval might be compensated by other variables. Therefore the effect on the retrieved wind has been simulated for three situations and the results displayed in Fig. 12. The base of these simulations were ozone profiles reduced by 10% with a vertical oscillation with a wavelength of 20 km and an amplitude of 5% of the ozone mixing ratio (referred to as "ozone variation" in Fig. 11) a control run with 1% reduction and 0.5% oscillation (referred to as "weak") and an extreme case with 30% reduction and 10% oscillation (referred to as "strong"). It appears that even such drastic differences between ozone a priori and true profile have very little effect on the wind retrieval.

Finally, one could think that differences in ozone profiles measured under different azimuths could have an effect on the wind profiles determined by WIRA, because their determination relies on the combination of measurements taken under two different azimuth angles (west and east for zonal, north and south for meridional wind). This effect has been quantified to be smaller than 1 $m\,s^{-1}$ on every altitude level when assuming that the ozone profiles between the two

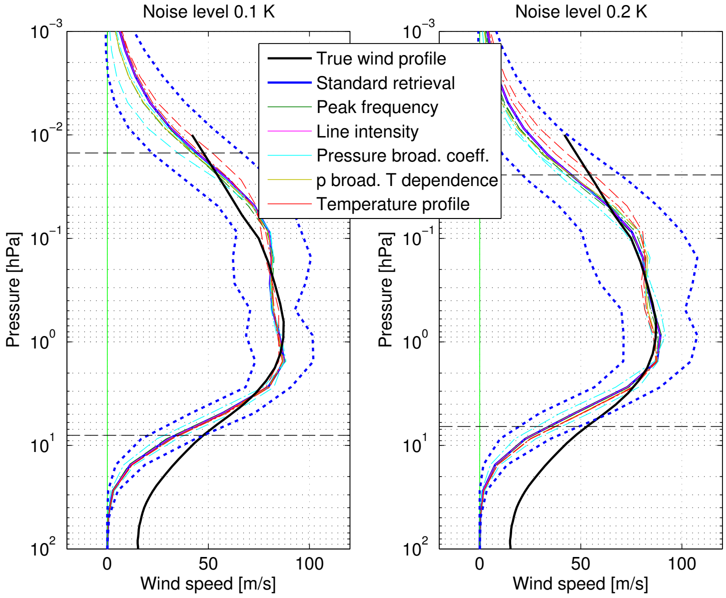


Fig. 11: As Fig. 10, but for the new single sideband receiver. This plot moreover contains the mean profiles resulting from retrievals with perturbed forward model parameters.

directions used for the wind retrieval are smaller than 5%, which seems a reasonable assumption with our observation geometry. For these calculations the part of the averaging kernel matrix relating ozone and wind has been used.

As mentioned in Sect. 2 the effect of fluctuations of the frequency references of the receiver on the measured wind is marginal.

Pickett, H. M., Poynter, R. L., Cohen, E. A., Delitsky, M. L., Pearson, J. C., and Muller, H. S. P.: Submillimeter, Millimeter, and Microwave Spectral Line Catalog, J. Quant. Spectrosc. Ra., 60, 883–890, doi: 10.1016/S0022-4073(98)00091-0, 1998.

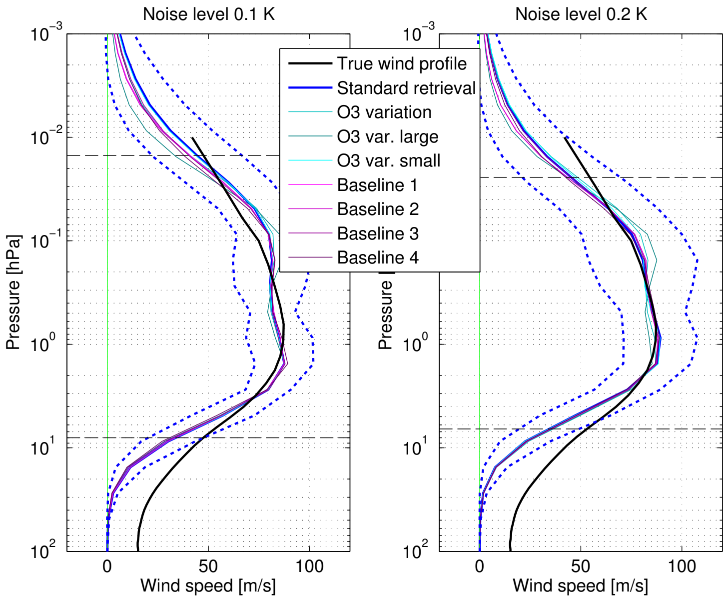


Fig. 12: As Fig. 11. Instead of the results for perturbed forward model parameters the mean profiles for situations with atmospheric ozone profiles strongly deviating from the a priori are plotted. The graph also contains the mean profiles for input spectra which are affected by a baseline with a typical amplitude and period for WIRA. Baseline 1, 2, 3 or 4 refers to baselines with different phases, i.e. which are shifted in spectral dimension.