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Atmospheric
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Interactive comment on "Polar night retrievals of trace gases in the Arctic using the Extended-range Atmospheric Emitted Radiance Interferometer" *by* Z. Mariani et al.

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Thank you for your work in helping us improve the manuscript. Our responses to both reviewers outline the changes made to the manuscript and are copied below. In the revised manuscript, text highlighted in yellow corresponds to the changes made in response to reviewer #2.

Response to Reviewer #1

April 13, 2013

Thank you for your review.

Response to Reviewer #2

April 13, 2013

Thank you for your comments, which have helped us improve the manuscript. We have responded to all comments below.

- *Title 'Polar night retrievals . . . ': Since the paper discusses retrievals from E-AERI during the whole year, this part of the title appears a bit too restrictive.*
  - We have changed the title to 'Year-round retrievals. . . '
- *P554L22: so-called "dirty window" around 400cm^{-1} where much of the infrared cooling to space occurs': it should be specified which 'cooling to space' is referred to here – since it is not the cooling of the Earth surface (which occurs in the IR window) but of higher atmospheric regions.*
  - Because of the extremely cold and dry Arctic atmosphere, this spectral region becomes more transparent and contributes to the cooling of the Earth's surface to space. See for instance {Clough, S. A., M. J. Iacono, and J.-L. Moncet (1992): Line-by-Line Calculations of Atmospheric Fluxes and Cooling Rates: Application to Water Vapor, J. Geophys. Res., 97, 15,761-15,785}, {Tobin, D.C., et al. (1999). "Downwelling spectral radiance observations at the SHEBA ice station: Water vapor continuum measurements from 17 to 26μm," *JGR* 104(D2): 2081-2092}and {http://asr.science.energy.gov/science/research-highlights/RMjk=/view}: "In the cold, dry conditions in the Arctic, this region becomes transparent and strongly influences the near surface contribution to the infrared cooling to space. . . at these lower temperatures, the peak of the Planck function shifts to longer wavelengths and subsequently the transmission properties of the atmosphere in this spectral region are crucial for climate and energy balance related issues." To clarify this, the text has been modified.

- *P557L8 'While in solar absorption spectroscopy the right most term in Eq. (3) can be neglected': It should be made clear, that this statement strongly depends on the opacity of the atmosphere at distinct wavelengths. E.g. at optically thick regions of the atmosphere this term cannot be neglected.*
  - It is now stated that it cannot be neglected at optically thick regions of the atmosphere.
- *P559L7 'uniformly shifted (increased/decreased)': What is ?tted: a scaling factor or an additive offset?*
  - A scaling factor is used; this is now clarified in the text.
- *P559L10 'to the lack of vertical sensitivity': I believe that pro?le information through the line shape is lost by the coarse spectral resolution. However, for broad windows with variable optical thickness there should still be information on the pro?le through different optical depths at different wavenumbers (like in IR nadir sounding from satellite). This is certainly the case for temperature retrieval in the 15 m CO_2-band but also most probably for ozone in the 10 m band and perhaps for CH_4 or N_2O. Could you comment on this?*
  - This is correct; the main reason for not getting altitude-resolved information is the coarse resolution. Profile retrievals of O_3, CO, CH_4, and N_2O were originally attempted using the relatively wide miniwindows which include a range of radiances but encountered several difficulties and overall did not perform as well as the scaled retrievals (spectral fits were worse, convergence problems were encountered, and there was insufficient DOFS (<1) for some retrieved spectra). Wider miniwindows cannot be used since the number of interfering species that would have to be fit exceeds the allowable limit (9) for SFIT2. Averaging kernels calculated for profile retrievals (see further comment) also indicated no information above ~5 km for CO, CH_4, and

N_2O (~20 km for O_3), reducing the usefulness of performing profile retrievals or calculating partial columns.

- *P558L18 'Sa, which constrains the retrieval to the a priori, was set to 30% for each target gas': Why is it set so stringent? For a retrieval of only column amounts, i.e. where no vertical pro?le information is retrieved but only a scaling factor, I would expect that no constraint at all is needed. I would strongly urge the authors to perform retrievals without any constraint or at least with a very loose one (e.g. 1000% a priori error) to see the in?uence of the a-priori. Further, in Fig. 3 and Fig. 6 there are results at the very edge of the a-priori assumption. To see how much information comes from the measurement compared to the a-priori, e.g. the degrees of freedom should be shown.*
  - Retrievals have been performed with Sa $=$ 100% and only small changes within the uncertainty were found in the retrieved total column for O_3, CO, CH_4, and N_2O compared to the retrievals using Sa $=$ 30%. Retrievals with Sa $=$ 1000% had larger differences compared to the columns retrieved with Sa $=$ 30%, but this is expected since the retrieval is no longer constrained. Due to the nonlinear nature of the retrievals using emission spectroscopy, strong constraints are necessary. The value of 30% was chosen because it optimized the retrieval results (provided the smallest residuals in the spectral fit while permitting the retrieval to converge on the final solution). The value of Sa is based on the maximum variability observed in the troposphere (where the E-AERI has sensitivity) in different climatological datasets used to derive Sa for solar absorption FTIR retrievals at Eureka: over 7000 HALOE (Lat >65°N) profiles from 1991-2005 were used for CH_4{Park et al., 1996; ref. now in manuscript}; the Eureka ozonesonde archive (1992-2005) and HALOE were used for O_3 (averaged ozonesondes up to 35 km alt., HALOE >35 km) {Lindenmaier et al., 2010; ref. in manuscript}; MkIV balloon measurements made at the high-latitude NDACC

site at Kiruna, Sweden were used for CO; and monthly mean VMRs reported in the SPARC2000 compilation (Lat >68^{o}N) were used for N_2O {Randel et al., 2002; ref. now in manuscript}. These details are now mentioned in the manuscript. Bruker 125HR retrievals use similar constraints: 20% for CO and CH_4, 30-70% for O_3, and 50% for N_2O, as shown in Lindenmaier [2012] (ref. in the manuscript). A plot of the total column averaging kernels has been added (see further comment) and indicates that the a priori contributes heavily only at higher altitudes. Since these are scaled retrievals, by definition the DOFS $= 1$ (mentioned in the manuscript).

- *P559L26 'The signal-to-noise ratio (SNR)': How is SNR de?ned here? It is stated as a single value, however, in thermal emission sounding, it should be very different at different wavenumbers (e.g. very small where there are no emission lines). The use of SNR probably makes sense in case of solar absorption measurements where the signal is on a constant high level. But in case of thermal emission observations the NESR (which varies much less than SNR with wavenumber) should be the correct quantity to set up the Sε matrix as it is standard e.g. for limb-emission sounding from satellite or balloon. Could you justify your choice?*
  - The SNR is defined here as the maximum radiance emitted by the target trace gas within the miniwindow divided by the noise (determined by the NESR) averaged throughout the miniwindow. Since the NESR varies only slightly with wavenumber, averaging the NESR throughout the miniwindow does not introduce any problems. The SNR does vary depending on the season (radiance increases in the summertime, thus the SNR increases in the summer). The NESR was used to set up the Sε matrix (see further comments).
- *P559L6 'This technique is described in more detail in Rodgers (2000)': Could you specify more precisely where in the book of Rodgers (2000) this is described?*

  - The section number was 4.5, but the reference to this technique is no longer necessary since this text has been removed as a result of the next comment.
- *P559L26-P560L7: This adaptation of Sε can be seen as the search for an optimum regularization parameter. However, in theory, Sε should only contain the variance derived from the estimated NESR values. Any regularization is normally performed by adaptation of Sa. Could you defend your approach in that respect.*
  - We apologize that the text was incorrect; the diagonals of Sε $=$ noise^2 and not 1/SNR^2. The noise is determined by averaging the NESR throughout the miniwindow (as discussed in a previous comment). The text in this section has been corrected.
- *Sect. 3.1 general: Have there been any ?t parameters apart from the pro?le scaling factors, like a baseline-offset to account e.g. for continuum of non-detected clouds? (The residual spectra in Fig. 2 are so nicely distributed around zero, that I've the impression that some wavenumber-constant offset has been jointly ?tted).*
  - An independent wavelength shift parameter for each miniwindow is used and the background slope is fit; this has been included in the text. The cloud filtering process is extremely conservative (and has been independently verified by using the Millimeter Cloud Radar and the Arctic High Spectral Resolution LIDAR) in order to remove any spectra that might contain thin clouds or fog.
- *P560L23 'Table 1 lists the optimal miniwindow selected for each trace gas': What is meant with 'optimal' in this respect? Has an optimization algorithm been applied?*
  - 'Optimal' is perhaps not the correct word; these are the miniwindows that resulted in the best spectral fits and highest retrieval convergence rates by

incorporating the largest number of strong emission lines from the target trace gas while reducing the amount of interfering species. The word 'optimal' has been removed in the manuscript to clarify this.

- *P560L25, Table1 'and the typical RMS residual in the spectral ?t': Since radiances are ?tted I would expect the RMS in radiance units. However, it is given in percent. So how is it de?ned? I would like to see it relative to the estimated NESR derived from calibration measurements (i.e. the chiˆ2) to be able to estimate the quality of the ?t.*
  - The RMS stated was the square root of the mean of the residual squared divided by the radiance. We agree that it makes more sense to state the RMS in radiance units and have changed it throughout the manuscript accordingly.
- *Fig. 2: The residuals e.g. in case of N_2O and CH_4 seem not only to contain spectral noise since these are rather variable with wavenumber. Could you elaborate on this? There is probably a problem connected to the instrumental line-shape (ILS). It is important to specify in the text how the ILS has been determined and how it is handled in the forward model. Has there been any kind of additional apodisation applied?*
  - The variability of the spectral fit residuals with wavenumber is not uncommon; for instance, see the residuals in the spectral fits for the Bruker 125HR in Batchelor et al. [2009] and CO retrievals using a different AERI in Yurganov et al. [2010] (ref. in the manuscript). The spectroscopic database used to fit these emission lines (HITRAN) has errors for each spectral line which vary with wavenumber. Specifically, the CH_4 lines are well-known to have large uncertainties that can attribute to larger residuals. The SFIT2 retrieval algorithm does not incorporate aerosols into its spectral fits; thus aerosols with emission signatures in certain regions (particularly the CO

miniwindow) will cause larger, broad residuals that vary with wavenumber. Another source of large residuals is due to H_2O lines; H_2O profiles are provided by the radiosondes but have large errors in the Arctic (discussed in Mariani et al. [2012], ref. in the manuscript), thus there may still be large residuals in the spectral fit even when these H_2O profiles are scale-fitted. A discussion of the ILS and the reference explaining the correction methodology of the instrument's self-apodization is now provided in Sect. 2.1. Unfortunately we are not currently equipped to perform ILS measurements with a gas cell. The SFIT2 algorithm applies the boxcar self-apodization due to the instrument but no additional apodization is applied.

- *P561L12 'Under this approach, the smoothing error (due to interpolation), Ss, and measurement error (due to noise), Sm, are added in quadrature with the forward model parameter errors and interference errors.': 1.) As written e.g. by Rodgers (2000), p.49: 'to estimate the smoothing error covariance, the covariance matrix of a real ensemble of states must be known'. Since for Sa a value of 30% has been used in general for all gases, the smoothing error which is given here seems wrong. It can only be correct if the real height-dependent covariance of the single gases would be used. 2.) Since $S\varepsilon$ has been determined like a regularisation parameter, the resulting Sm can also not be correct. For a correct determination of Sm the measurement NESR should have been used for $S\varepsilon$.*
  - 1) An estimate of the real height-dependent covariance of the single gases is provided by climatological datasets as discussed in Sect. 3.4 in Lindenmaier [2012] (ref. in manuscript). Thus Sa was not chosen using an ad hoc method. As discussed in a previous comment, HALOE, the Eureka ozonesonde archive, MkIV balloon measurements, and monthly mean VMRs reported in the SPARC2000 compilation were used to estimate Sa and xa for all four gases; these climatological datasets are now described in the manuscript. Since we cannot obtain the 'true' height-dependent co-

variance of the gases, these climatologies provide the best estimate of the true state and were used to generate the a priori profiles and Sa matrices used in the retrieval. Sa was held constant for all altitude layers in E-AERI retrievals and set to the value found in the troposphere, since this is where the E-AERI has sensitivity. If we use the full climatology's estimate of Sa (which varies with altitude), the largest increase in Sa is for stratospheric O_3 (~75% in the stratosphere), but the uncertainty for all trace gases in the troposphere (where the E-AERI has sensitivity) is around 30% (and in some cases <20%). Ss increases only slightly for each trace gas (<2% increase) when we use the climatology's estimate of Sa that varies with altitude, not significantly changing the total error budget.
2) The NESR was used for $S\varepsilon$ (as discussed in a previous comment) and, subsequently, Sm; the text has been corrected in this regard.

- *P561L14 'The noise equivalent spectral radiance (NESR) quanti?es the radiometric calibration error': The NESR in emission spectroscopy normally quanti?es the instrumental spectral noise while radiometric calibration is more a broadband effect with a relative (gain) and absolute (offset) error term. Could you explain your statement?*
  - The NESR reported here is the RMS noise for a 2-minute blackbody view expressed in units of radiance. The text has been re-written in this section to clarify this. Details of the radiometric calibration are provided in Mariani et al. [2012] (ref. in manuscript).
- *P561L21-26: It is not clear which temperature uncertainty has been used: Vaisala or ECMWF?*
  - The Vaisala temperature error was not used; instead a temperature uncertainty of $+2$ K was used below 30 km in the retrievals. Larger temperature errors than the Vaisala temperature error were used as a conservative estimate to account for the interpolation of the temperature profile on a coarse-resolution altitude grid (39 layers) and the time differences (only two radiosondes were launched during each day). The Vaisala temperature uncertainty has been removed to clarify this in the manuscript.

- *P264L1-17 ': : :of increased H_2O and scattered solar energy from aerosols during this season: : :': In case the aerosols are smaller than about the wavelength, scattering can be neglected and the effect in the emission spectrum is primarily that of broadband continuum emission. Only for larger aerosols scattering becomes important. This should be mentioned. Further, it would be good to compare a ?t in the summer with one in the winter since in presence of aerosols and/or H_2O continuum effects there should be a baseline offset in the residuum (this is connected to the question whether there is some additional baseline/offset ?t in the retrieval). From analysis it would be informative to see, like in Fig. 3, the broadband offset versus time in order to correlate with the apparently larger bias between HR125 and E-AERI in summer compared to winter.*
  - This discussion regarding aerosols has been added to the text. Figure 2 has been re-done to include summer and winter fits, allowing for a clear comparison between these seasons. The text has been altered in Sect. 3.2 to account for the additions to the figure.
- *P565L2: To prove this statement about the vertical sensitivity of E-AERI I would recommend to show e.g. the height-dependent averaging kernel of the retrieval for the different gases.*
  - We agree and have added a new figure showing the E-AERI and Bruker 125HR total column averaging kernels for each trace gas (now Fig. 4) and included an explanation in the text in Sect. 4.1. We have also included smoothed 125HR profiles by the E-AERI averaging kernel, included a brief

description of the smoothed profiles, and added this to the table of differences and correlation comparisons. There is significantly better agreement between smoothed 125HR CO measurements and the E-AERI (now Fig. 5b), for instance.

- *P565L3 'The day-to-day variability in the CH4 and N2O column is greatest in the summer': I cannot really spot this in Fig. 2 when comparing polar winter to summer. Could you make it more clear.*
  - The variability is apparent in Fig. 3 (and Fig. 6), not Fig. 2. We agree that this is very difficult to see from this figure since the observed increase in variability is very small and not statistically significant, so we have removed this statement.
- *P567L20 'Both of these amplitudes are larger than that in Oklahoma (40 %) (Yurganov et al., 2010), indicating a stronger 365-day seasonal cycle of CO at Eureka compared to mid-latitudes': Given the larger bias of CO vs. the HR125 in the summer, this seasonal cycle may be overestimated. How large is it for the HR125? This should be discussed.*
  - It is true that this seasonal cycle may be overestimated; this point is now included in the text. The 125HR does not take any measurements during polar night and only limited measurements during the summer of 2011. Because of this, the full seasonal cycle of CO as measured by the 125HR cannot be determined with a high degree of reliability.
- *P568L8 'The additional error due to this removal is small (<1 %) for all trace gases. The removal of the ?rst 600m has a large effect on tropospheric trace gas species, such as CO, which are heavily concentrated within the ?rst 600m (20%) compared to stratospheric species, such as O_3 (0.6% at Eureka).': I don't understand why the additional error should be small when in the next sentence*

it is stated that the effect of the removal is large. Since one does not know the altitude pro?le, I assume that the error for tropospheric trace gases could also be larger than 1%.

  - Parts of this text have been removed and/or changed to make this more clear, as we agree that these two points are confusing when put together. Removing the first 600 m reduces the total column concentration of tropospheric species by a larger amount than for O_3, as one would expect. The 'additional error due to this removal' mentioned was determined by generating simulated spectra and corresponding 'true' profiles of the trace gases, computing the 'true' total columns, and then retrieving total columns using the simulated spectra (with noise added). The first 600 m of the atmosphere was removed from 'true' and retrieved total columns, and a comparison in the magnitude to which the total columns changed was made. When the first 600 m is removed (the bottom layer of the 39-layer altitude grid that the retrieval uses), the difference between the changes in the simulated and retrieved total columns (ΔsimulatedTC - ΔretrievedTC) is <1%. The largest difference out of a set of simulated retrievals performed for all trace gases in different seasons was 1.4% (CO in the summertime); for this reason the text will be corrected to (<2%).
- *Fig. 6: For CH_4 and N_2O there is a clear positive bias in the summer compared to Fig. 3 and the HR125-measurements. Could you comment on this?*
  - The positive bias in 2011 is not outside the experimental uncertainty, and since no 125HR measurements were conducted over a two-month period surrounding the E-AERI July measurements (down for repairs), it is difficult to perform further comparisons. However, the positive bias may be the result of the additional water vapour at 0PAL, since it occurs in mid-July when the water vapour concentration at Eureka is at a maximum. This additional wa-

ter vapour is difficult to fit accurately (as discussed in the manuscript), and SFIT2 may be incorrectly attributing the additional H_2O emission towards CH_4 or N_2O total columns. Aerosol concentrations are also at a maximum during this time, and their emission signatures occur within the CH_4 and N_2O miniwindows. This additional emission from aerosols is not accounted for in the SFIT2 retrieval algorithm (as discussed in the manuscript). Hence the apparent positive bias is likely due to the enhanced influence that increased aerosols and water vapour concentrations have at lower measurement altitudes (0PAL vs. PEARL) on the retrieval; this is now mentioned in the text.

- *P579L11 'RMS residuals <1.5 %.': 1.5% relative to what? Since there are small and large emission lines, as stated above, I think a relative value is not very sensible here. It could better be given relative to the NESR.*
  - The text has been changed to reflect the new RMS units (as discussed in a previous comment).
- *Fig. 7: In this scatter-plot the E-AERI column amounts of O_3 look kind of 'binned' i.e. the same value of E-AERI for different values of 125HR (and sometimes vice-versa). Are these different values of HR125 for the same E-AERI column? This should be stated at least in the caption. If this is the case, can such correlated pairs be used in the same way as fully uncorrelated ones for calculating the statistical parameters as given in the plots?*
  - E-AERI and 125HR values were not binned, as this would incorrectly generate additional correlations, impacting the Pearson correlation coefficient. 125HR measurements were averaged when multiple 125HR measurements occurred during the three-hour coincident criterion and matched with an E-AERI measurement. In the event that multiple E-AERI and 125HR measurements occurred within the three-hour window, the closest pairs were selected. The apparent binning may be the result of the relatively constant

hourly concentration of the trace gas, particularly during periods of polar night and winter when there is no solar cycle (for instance, O_3 concentrations remain relatively constant throughout the day during polar night/day). The figure also originally used total column concentrations that were rounded to low precision; the figure has been re-done using the appropriate significant figures.

- *P553L12: Since there are different de?nitions of resolution, please de?ne which value this de?nition of resolution refers to (since sometimes 1/2L and sometimes 0.61/L (FWHM) is used).*
  - Resolution refers to 1 / maximum OPD; this is now stated in the text.
- *P557L6 'of the layer': Change to 'from the layer'*
  - This change has been made in the text.

Interactive comment on Atmos. Meas. Tech. Discuss., 6, 547, 2013.