GMD-2017-303

Interactive comment on "Comparison of observed and modelled longwave radiation (2010-2016) at the high mountain BSRN Izaña station" by R. D. García et al.

Dr. Slimane Bekki

This paper presents a comparison between observed and modelled LDR from 2010 and 2016 at the Izana station for both day-time and night-time. I really enjoyed reading this paper, which is quite clear and presents very interesting and important results for the community. I do recommend this paper for publication, but after some minor revisions. I have also some few questions that need to be addressed and could improve the paper. I have only one major comment about the paper regarding the way the authors are estimating the uncertainty of the models (section 4.2).

Authors: We appreciate the positive feedback and constructive comments of the Editor. The major comment regarding the estimation of the models uncertainty is addressed hereinafter.

Specific comments/questions:

Page 1 lines 16-17: Are there any more recent reviews regarding the anthropogenic greenhouse gas?

Authors: Following the Editor's recommendation, the authors have added the following references: Iacono et al., (2008), Philipona et al., (2012), Wang and Dickinson (2013), Wild et al., (2013), Wild et al. (2015).

Page 1 line 18: What are the uncertainties required on LDR measurements to assess completely their impact on climate changes?

Authors: We have added the following paragraph to the final section of summary and conclusions:

> *"Considering that the BSRN measurement accuracy target for LDR is ±2 Wm^{-2}, the average observed LDR change from 24 BSRN sites since early 1990s has been +2 Wm^{-2} dec^{-1} (Wild, 2017) as a result of the increase of the greenhouse effect, and the CMIP5 projections estimate LDR increases between 1.7 Wm^{-2} dec^{-1}(RCP4.5) and 2.2 Wm^{-2} dec^{-1} (RCP8.5) over the period 2010-2013 (Wild et al., 2015; 2017), it is crucial to ensure good consistency between LDR observations and estimates with models, such as the one found in this study. We can say that with the present LDR measurement accuracy, a period of*

time less than two decades would be necessary for assessing completely its impact on climate change".

Page 2 line 4: Could you specify how much represents 7.5 Wm^{-2} over the [4-42 micrometer] band?

Authors: Note that the sentence "…The spectral range covers from 4 to 42 µm with an expected sensitivity of 5 to 15 $\mu V/Wm^{-2}$, an uncertainty < 3% for daily totals, and an estimated inaccuracy < 7.5 Wm^{-2} (Kipp and Zonen, 2014)…" has been removed following the Referee#1's suggestion (see Response Referee #1).

Page 2 line 13: "Stefan-Boltzmann" is misspelled wrongly several times within the paper.

Authors: Done.

Page 4 Figure 1: Can you explain what the physical meaning of the upper and lower limit?

Authors: The upper and lower limits (Physically possible (PP): 40-700 W/m^2 and Extremely rare (ER): 60-500 W/m^2) correspond to black body temperature of -100°C and 60°C (Gilgen et al., 1995; Long and Dutton, 2002).

Page 4 lines 5-6: You are mentioning the calibration date of the instruments. How do these instruments degrade over time (% per year)? Has been any degradation characterization?

Authors: We appreciate this comment, whose answer is very timely to include in the manuscript.

Yes. We have estimated the degradation of the pyrgeometer using to consecutive calibrations performed in June 2014 and March 2017. The change in the calibration coefficients is 0.21% in 2.75 years, so the degradation is 0.08%/yr.

We have included the following text in Section 3.1, and modified Table 1 accordingly.

> *"In this study, we analyzed measurements performed with two CG(R)4 series (see Table 1) between 2010 and 2016 at IZO. The CG(R)4 #080022 was calibrated by the manufacturer in February 2008 at Holland (Kipp & Zonen) and the CG(R)4 #050783 was calibrated in June 2014 and March 2017 at the Physikalisch-Meteorologisches Observatorium Davos/World Radiation Center (PMOD/WRC). Given the two calibration coefficients of the second instrument (see Table 1), we estimate that its degradation is very small, lower than 0.08%/yr."*

Page 5: There is no need for a 3.0.1 title here.

Authors: Done.

Page 5: from your regression study, it is possible to estimate the uncertainty about ε_AD.

Authors: Following the Editor's recommendation, the authors have added the uncertainty of ε_{AC}: $\varepsilon_{AC}=(0.218 \pm 0.05)+(0.385 \pm 0.07)x^{1/8}$

Page 7 line 6: why do you consider the spectral range from 4 to 100 micrometer, when your spectral band of interest is [4-42] micrometer?

Authors: The spectral response function of a pyrgeometer normally covers a wavelength range from 3.5 mm to about 50 mm. However, pyrgeometers are calibrated in the total range of terrestrial longwave emission (4 to 100 µm).

Page 7: I found the section 4.1 about the input parameters a bit confusing to follow, and I would suggest organizing things a bit more neat. The text would be easier to follow if the input parameters are presented as a clear list, with an equivalent structure.

Authors: Following the Editor's recommendation (Pag 7 and Pag 10, 6-7), the authors have modified and clarified the Section 4 as follows:

SECTION 4: RADIATIVE TRANSFER MODELS AND INPUT PARAMETERS

"The simulations of surface LDR were determined with two RTMs: libRadtran and MODTRAN. The LibRadtran model (freely available from http://www.libradtran.org; Mayer and Kylling (2005)) used in this work is the version 2.0.1 (Emde et al., 2016). The simulations were performed with highly resolved absorption coefficients that were calculated using the absorption band parameterization called REPTRAN. It is based on the HITRAN 2004 spectroscopic database, in which wavelength-integrals have been parameterized as weighted means over representative wavelengths (Gasteiger et al., 2014). The simulations performed using REPTRAN in the thermal range showed relative differences of about 1% with respect 5 to simulations performed with high spectral resolution models and they are 6-7 times better than the simulations done with the LOWTRAN band parameterization (Gasteiger et al., 2014).

The MODTRAN version used in this work is the MODTRAN v6 (Berk and Hawes, 2017), an atmospheric transmittance and radiance model developed by the U. S. Air Force Research Laboratory in collaboration with Spectral Sciences, Inc. We have selected a band model with a resolution of 1 cm^{-1} for spectral calculations. The MODTRAN band model molecular spectroscopy is based on the HIgh-resolution TRANsmission molecular absorption (HITRAN) database (Rothman et al., 2013).

For both models, the LDR simulations were calculated by using as radiative transfer equation (RTE) solver the DISORT (DIScrete ORdinate Radiative Transfer solvers), developed by Chandrasekhar (1960) and Stamnes et al. (1988, 2000), and based on the 5 multi-stream discrete ordinates algorithm. The number of *streams used to run Disort was 16. For each simulation, the integrated downward irradiance has been calculated in the spectral range 4-100 µm.*

The two models were run using the same inputs, atmosphere and geometry in order to minimize.

The rest of the inputs measured at IZO are:

- *Radiosondes: Temperature and relative humidity (RH) profiles*

  In this work, we have used the AEMET's meteorological radiosondes dataset. Radiosondes are launched twice a day, at 11 and 23 UTC at the Güimar station (WMO GRUAN station #60018, 105 m a.s.l.). This station is located at the coastline, approximately 15 km to the southeast of IZO. Vertical profiles of pressure, temperature and relative humidity were obtained with Vaisala RS92 radiosondes (Rodríguez-Franco and Cuevas, 2013; Carrillo et al., 2016). We have used the radiosonde profiles from the altitude of IZO (2373 m a.s.l.).

- *PWV*

  Since January 2009, the PWV has been obtained every 1h at IZO from a (Global Navigation Satellite System (GNSS) receiver considering satellite precise orbits (Romero Campos et al., 2009). In this work, we have used the PWV median measured between 11-13 and 23-01 UTC in order to take into account the radiosonde flight time, and hence making possible a comparison with GNSS observations.

- *N_2O and CO_2 profiles*

  The volume mixing ratio (VMR) profiles of atmospheric CO_2 and N_2O trace gases were used. These were obtained from the monthly average profiles performed with the ground-based Fourier Transform InfraRed spectrometer (FTIR) at IZO between 1999 and 2015 (Schneider et al., 2005; García et al., 2014; Barthlott et al., 2015). The FTIR program at IZO is part of the Network for the Detection of Atmospheric Composition Change (NDACC). In this study FTIR climatological profiles have been used. The profiles were scaled on a daily basis with ground-level in-situ CO2 and N2O mixing ratios, continuously measured at IZO since June 1984 and June 2007, respectively, within the WMO GAW programme (Cuevas et al., 2015, 2017).

- *In-situ N_2O and CO_2*

  Since 2007 the CO_2 in-situ measurements have been performed with a NDIR analyzer (LICOR-7000) (Gómez-Peláez and Ramos, 2009; Gómez-Peláez et al., 2010) and the N_2O in-situ measurements with a VARIAN (GC-ECD 3800) (Scheel, 2009). We have used in this work only the night-time (20-08 UTC) averaged CO_2 and N_2O data because during this period IZO is under background free troposphere conditions, and the observatory is not affected by local and regional sources of such gases.

- *AOD*

Atmospheric aerosols have been included in the simulation process by means of the column-integrated aerosol optical depth (AOD), extracted from AERONET (Level 2.0 of version 2, cloud screened and quality ensured). AOD is obtained from solar observations performed with CIMEL sunphotometers at different wavelengths (Holben et al., 1998; Dubovik and King, 2000; Dubovik et al., 2006). The Shetle's aerosol model (Shettle, 1990) has been used in this study. The default properties are: rural type aerosol in the boundary layer, background aerosol above 2 km, spring-summer conditions and a visibility of 50 km. In this work, AOD at 500 nm has been used as model input. For day-time we have used the nearest AOD value to 11 UTC, and for night-time the last available AOD value of the day.

- *Total ozone column (TOC)*

TOC measurements with Brewer spectrometer began in 1991 at IZO. Since 2003 IZO has been appointed the Regional Brewer Calibration Center for Europe (RBCC-E; http://www.rbcc-e.org) and the total ozone program has been part of NDACC network. We have considered daily total ozone mean value as model input."

Page 8 about the section 4.2: the method used by the author to estimate the uncertainty is rather simple, and is not statistically relevant and I would strongly advise the authors to change their method. A Monte-Carlo approach considering a normal distribution for each uncertainty parameters would definitely give a more appropriate estimate of the RT model global uncertainty. It requires however more computing time than the one run approach from the authors. In that case, the table 3 is no longer needed and can be replaced by a much smaller table resuming the global uncertainty using a Monte-Carlo approach.

Authors: The authors have followed the "*Guide to the Expression of Uncertainty in Measurement*" (GUM) to estimate the RTM uncertainty in this work. This guide establishes general rules for evaluating and expressing uncertainty in measurement, and states the uncertainty can be evaluated by means of the statistical analysis of our observations (Type A evaluation). The combined standard uncertainty is therefore obtained from the positive square root of the sum of the different contributions. A least squares fitting has been performed to estimate these individual contributions. This approach was first applied by Rodgers (2000), and later is described in many references in the literature, (Schneider and Hase 2008; García et al. 2014, Schneider et al. 2006). Rodgers (2000) demonstrated that it is possible to separate systematic and random errors from a least squares fit of errors (Sim + δ) versus un-perturbed values (Sim). The slope of the regression fit can be identified as a systematic sensitivity error while the offset can be assumed as a systematic bias error. The random error is evaluated by means of the scatter around the regression line. Looking at these references, the authors consider that this method is statistically relevant despite being simpler than a Monte Carlo approach.

As Belluardo et al. (2016) claimed, fewer studies exist on how much the input uncertainty propagates into the radiative transfer code simulations. Monte Carlo technique seemed to them a more efficient way to study their uncertainty, but they also admitted there are other ways to estimate these uncertainties in which possible correlations between these inputs parameters are properly taken into account.

We have seriously considered addressing an uncertainty analysis with the Monte Carlo method, as proposed by the Editor. However, an estimate of the number of simulations that are necessary to perform the RTM uncertainty with this approach shows us that we would need more than 4.000 model runs (2 model inputs, 500 trials, day-time, night-time, 2 RTMS, plus parameters combination) varying only the most important input parameters (PWV and AOD) since the contribution to the total uncertainty of the rest of the parameters is negligible. In addition to all this, and as has been answered to Referee#1, we could not address the inaccuracies in the observed temperature/humidity profiles due to different heating of the radiosonde sensors by solar radiation, which might be a clear uncertainty source. On the other hand, the agreement between RTMs is quite good (MB <1 Wm^{-2}, 0.4%), very similar to the uncertainty estimated for both RTMs (<0.95 Wm^{-2}, 0.5%) which suggests that the estimation of the uncertainty estimated with the GUM approach is reasonable.

These results don't justify a more complex calculation of the uncertainty with a computational cost so high. An analysis with the Monte Carlo Method would constitute a study (and a publication) itself, and we cannot address it in this study.

Page 8 Table 3: the combined uncertainty for Modtran model is wrong (I guess a copy-paste from the combined uncertainty for the LibRadtran model).

Authors: Corrected.

Page 10 lines 6-7: Could you explain the main differences between the two models? It is not clear at all what makes these two RT models different, and the excellent comparison with the BSRN data does not shed much light about the RT performances differences.

Authors: We have included the following text into the manuscript:

> *"The main differences between the two models is in the molecular absorption band: while MODTRAN uses High-resolution TRANsmission molecular absorption (HITRAN) database (Rothman et al., 2013), LibRadtran uses the absorption band parameterization called REPTRAN (Gasteiger et al., 2014)."*

Page 11 Table 4: Please change R -> r for the Pearson correlation coefficient. Why showing the correlation coefficient r and not R^2, which in your case of a linear regression is the square of r. R^2 represents the proportion of variance that can be explained by the linear regression. For day time with BSRN/LibRadtran, R^2 = 0.962 so 3.8 % of the variance is not explained by the linear regression. Also, why do the authors mentioned here the STD, since there is no reference within the text? What more information can bring the STD here when this clearly the RMSE that is valuable for the authors?

Authors: Following the Editor's recommendation, the authors have removed STD from Table 4 and have used R^2 in the manuscript.

Page 11 line 10: I cannot find any mention of the LOWTRAN model earlier in the text. Please introduce it by explaining the differences with MODTRAN and LIBRADTRAN. Same for the SBDART model.

Authors: References to both LOWTRAN and SBDART are done in the introduction of the manuscript (page 2). However, the authors do not consider it appropriate to describe LOWTRAN and SBDART since these RTMs are not used in this study.

Page 12 line 21-22: I do understand that this outside the scope of this paper, but the authors should discuss which are the further ways or analysis needed to understand those discrepancies. This would indeed considerably make the paper more valuable other than just a data set description (although valuable for the community).

Authors: The authors have added more information following the recommendation of referee 1 (see Response Referee #1) (see final manuscript uploaded on March 26):

> *"..The small differences observed in the evolution of the LDR bias with the PWV (close to the instrumental error) found between day-time and night-time are not currently understood. It is likely that this different behaviour between day and night may be associated with instrumental measurements (Ohmura et al., 1998; McArthur, 2005), but we do not preclude they could be also related to inaccuracies in the model input parameters during day-time, e.g., inaccuracies in the observed temperature/humidity profiles due to different heating of the radiosonde sensors by solar radiation. Dirksen et al. (2014) studied the effects on the RS92's temperature and humidity measurements and they estimated this uncertainty to be 0.15 K for night-time temperature measurements and approximately 0.6 K at 25 km during daytime…"*

Page 12: The authors presented box plot of bias versus PWV. And what about the same results versus AOD (2nd uncertainty source)? Would the authors find also a clear pattern as for the PWV?

Authors: The authors appreciate this suggestion. Specific analysis of bias dependence on AOD and PWV has been included in the paper as follows:

> *According to the results obtained in Section 4.2, the uncertainties on PWV and AOD dominate the total uncertainty, thus, the LDR bias have been analyzed.*
>
> *The box plot of LDR bias for different PWV is presented in Figures 4a and 4b. Both models tend to underestimate LDR (up to 5 Wm^{-2}) in the case of day-time measurements with PWV<9 mm (Figure 4a). A LDR bias around zero is observed for higher PWV, although it is necessary to emphasize that the number of data in this PWV range (between 4% and 5%) is much lower. At night-time, the dependence of LDR bias with PWV shows a negligible bias under dry conditions (PWV<6 mm), and a slight overestimation of both models (up to +5 Wm^{-2}) for higher PWV values (Figure 4b). These results are consistent with those obtained by Gröbner et al. (2014) and Nyeki et al. (2017) which argue that the World Infrared Standard Group (WISG) of pyrgeometers has a negative bias of about 5 Wm^{-2} under cloud-free conditions and PWV>10 mm.*

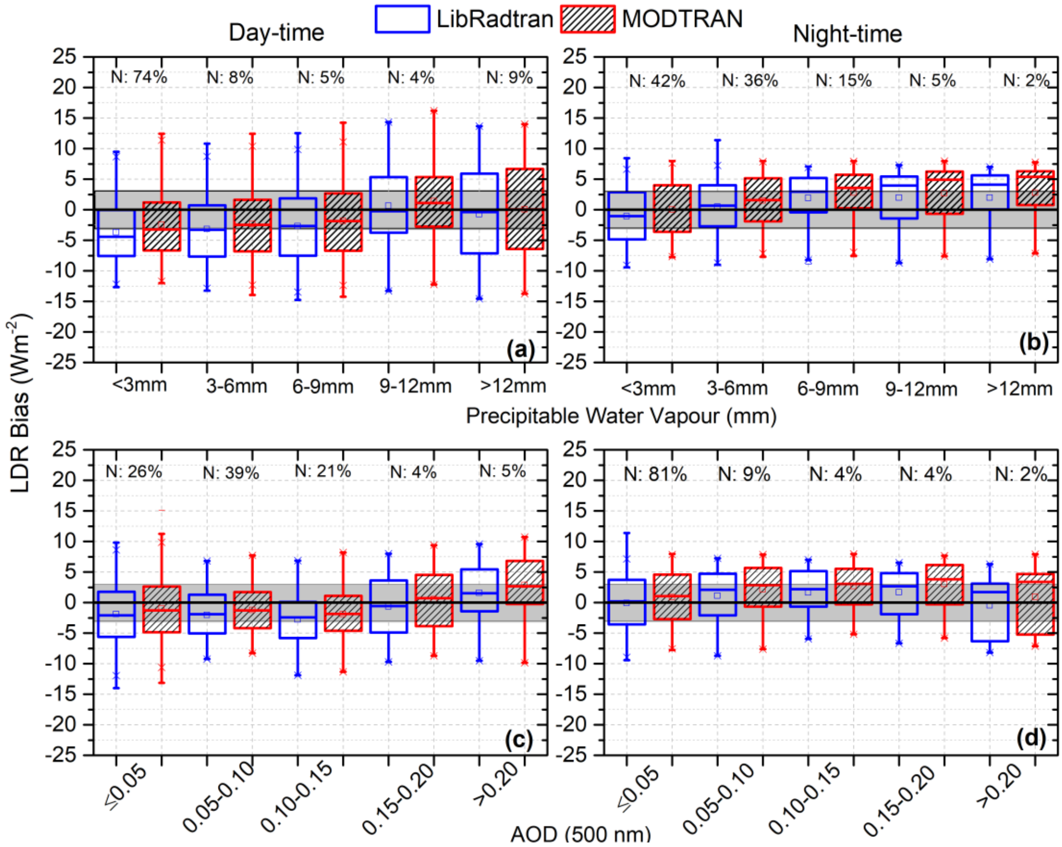

Figure 4. *Box plot of mean LDR bias (Model-BSRN in Wm^{-2}) versus PWV (mm) (a) at day-time, (b) at night-time and versus AOD (500 nm) (c) at day-time, (d) at night-time between 2010 and 2016. Lower and upper boundaries for each box are the 25th and 75th percentiles; the solid line is the median value; the crosses indicate values out of the 1.5 fold box area (outliers); and hyphens are the maximum and minimum values. The blue boxes represent libRadtran/BSRN and the red ones represent MODTRAN/BSRN. N indicates the number the measurements in each interval. Shadings show the range of instrumental error (±3 Wm^{-2})*

Similar results were observed in Figure 4c and 4d, where the dependence of LDR bias with AOD at 500 nm is shown. This may be due to the fact that PWV and AOD are not completely independent at the Izaña Observatory. In fact these parameters show a moderate correlation (R^2 = 0.27 in daytime and R^2 = 0.19 in night-time). The reason is that the Saharan Air Layer (SAL) intrusions into the subtropical free troposphere over the North Atlantic are not only associated with dust-laden air masses (higher values of AOD) but also with more content in water vapour (higher PWV) as described by Cuevas et al. (2013) and Andrey et al. (2014). The Saharan dust intrusions in the Canary Islands occur de the intrusions of Saharan dust in the Canary Islands have a pulsating character, especially in summer, alternating pristine days with periods of hazy days (Cuevas et al., 2017)

In order to separate the dependence of LDR bias with PWV from AOD, and vice versa, we have analyzed, on one hand, the LDR bias in function of PWV considering very low aerosols conditions (AOD≤0.05) (Figures 5a and 5b) and, on the other hand, the LDR bias in function of AOD for very dry conditions (PWV≤5 mm) according to WMO (2004) criteria (Figures 5c and 5d).

An almost flat negative offset in LDR bias is observed in the case of AOD≤0.05 day-time data for a relatively large range of PWV, while a larger positive bias is observed at night-time for higher PWV values (Figures 5 a and b, respectively). These results corroborate the dependence of LDR bias with PWV for all conditions found in Figure 4b.

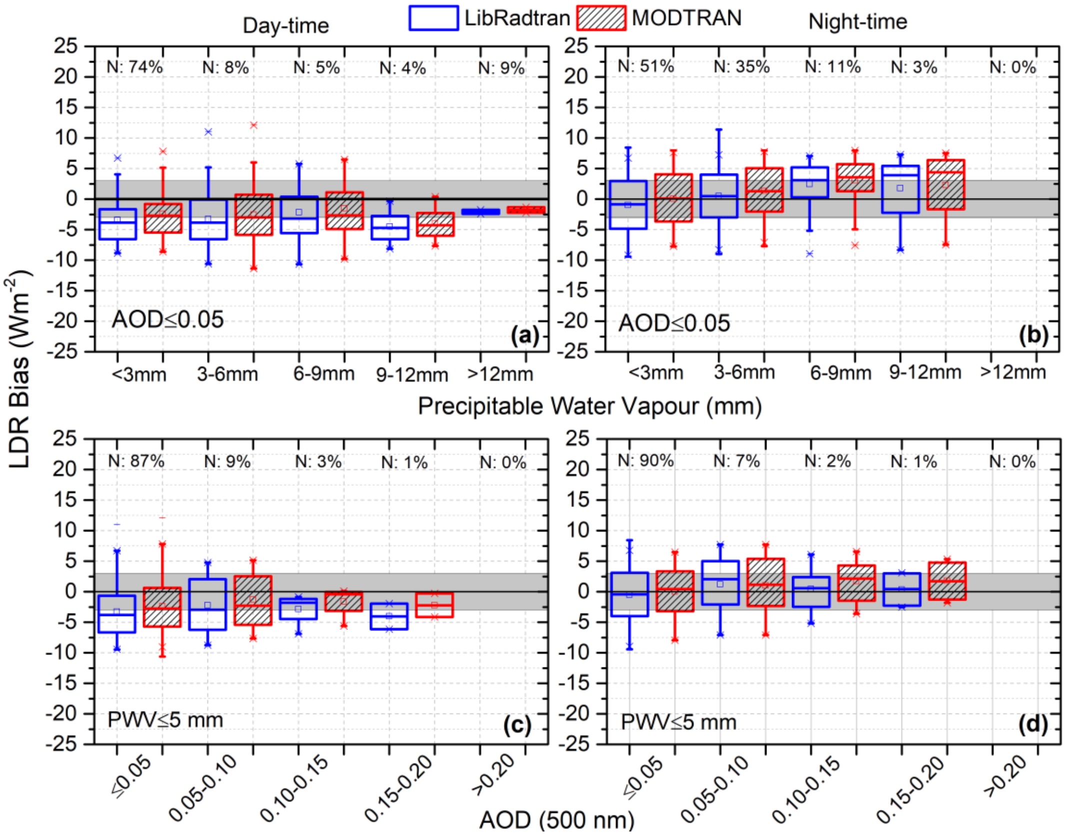

Figure 5. *Box plot of mean LDR bias (Model-BSRN in Wm^{-2}) versus PWV (mm) (a) at day-time, (b) at night-time for AOD≤0.05, and versus AOD at 500 nm (c) at day (d) night-time for PWV≤ 5 nm between 2010 and 2016 at IZO. Box plots are defined as in Figure 4.*

The small differences in LDR bias versus PWV (close to the instrumental error) found between day-time and night-time are not currently understood. It is likely that this different behaviour between day and night may be associated with instrumental measurements (Ohmura et al., 1998; McArthur, 2005) but we do not preclude they could be also related to inaccuracies in the model input parameters during day-time, e.g., inaccuracies in the observed temperature/humidity profiles due to different heating of the radiosonde sensors by solar radiation. Dirksen et al. (2014) studied the effects on the RS92's temperature and humidity measurements and they estimated this uncertainty to be 0.15 K for night-time temperature measurements and approximately 0.6 K at 25 km during daytime.

Concerning the LDR bias dependence with AOD for very dry conditions (PWV≤5 mm) (Figure 5c), we observe a nearly constant negative bias at day-time, similar to that found for clean conditions (AOD≤0.05) (Figure 5a), while the LDR bias versus AOD at nigh-time (Figure 5d) is almost zero.

Some authors claim that dust particles might modify the transport of both shortwave and longwave radiation through the atmosphere by scattering and absorption processes and that dust radiative effects in the infrared are thus non negligible (Otto et al., 2007; Meloni et al., 2018). Our results point to an increase in the LDR bias during daytime as the AOD increases (Figure 4c) which might mean LDR underestimation by the models which would not capture the aforementioned dust absorption and scattering processes. Notice that there is not equivalent positive trend in LDR bias for higher PWV values (Figure 4a), suggesting that this LDR bias trend is basically caused by an increase in atmospheric dust content. Unfortunately we cannot confirm these results in a dry atmosphere (removing the effect of water vapour) due to the lack of relatively high AOD data under PWV≤5 mm conditions (Figure 5c). It would be necessary to do specific research on dust effect in LDR performing additional model simulations for different sets of dust particle size distribution and refractive index, as proposed by Meloni et al. (2018), to confirm that the observed positive LDR bias for high AOD values during day-time is caused by mineral dust particles.

Page 13 Figure 5: What does represent the vertical dash line for January 2013? The authors mentioned in the text a "change point" for October 2012? I would also suggest here to add the histograms of the bias to have a better view of the distribution of the residuals. Assuming a normal distribution of the residuals, then the STD of table 4 would then be meaningful. But there is no reason that the distribution should be normal. Especially after what has been discussed with the impact of the PWV and the temporal stability.

Authors: *It is seems there is a confusion on this issue. The authors didn't add any line in January 2013. Probably this line appeared when exporting the Figure to eps format.*

On the other hand, and following the Editor's recommendation, the authors have added the histograms of the LDR bias. Given that the distribution is not normal, we have removed the STD in Table 4.

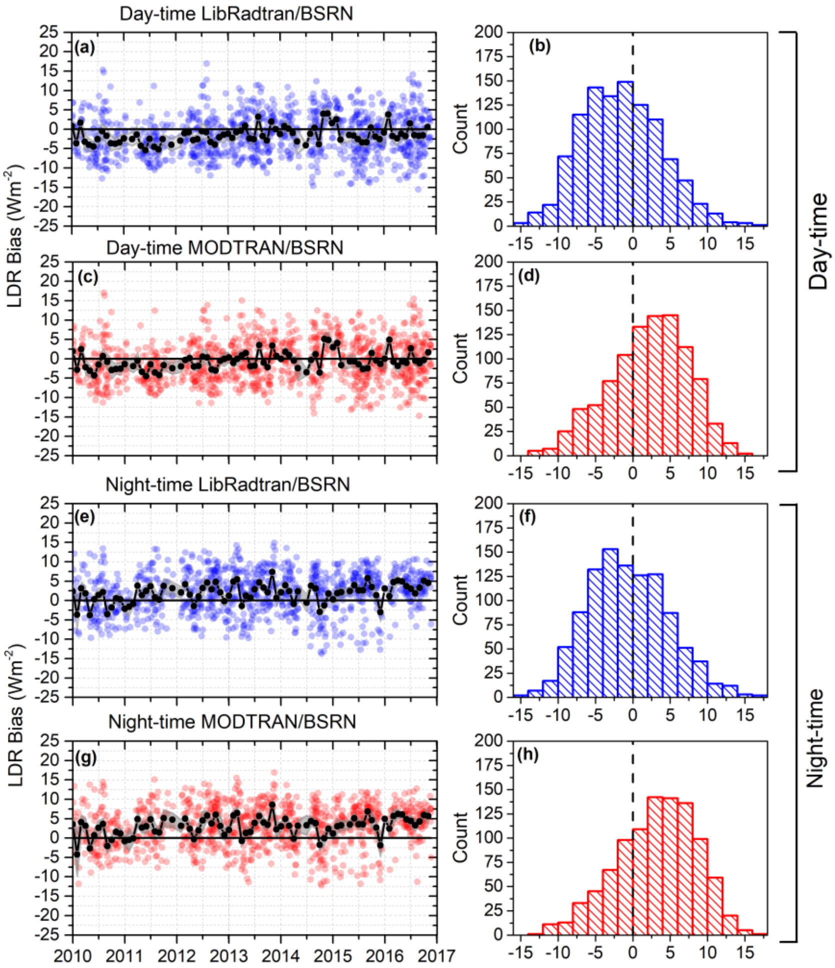

Figure 5.- Time series and histogram of bias (Model-BSRN in Wm^{-2}) between 2010 and 2016 at IZO. The blue and red dots represent the instantaneous LDR bias for LibRadtran/BSRN and MODTRAN/BSRN, respectively. The black dots represent the monthly mean LDR bias. The grey shadings show the range of ±1SEM (standard error of the monthly mean bias).

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