Reply on Referee #1 Stefan Wacker (AMT-2022-259)

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1 Introduction

The comments of the reviewer have been helpful to improve the manuscript. We are especially thankful for pointing at the comparison to radiative transfer simulations of the thermal-infrared downward irradiance and the missing literature. This provided some new aspects to quantify the performance of the radiometer systems. We think that this significantly increased the value of the manuscript for potential readers.
The detailed replies on the reviewers comments are given below. The reviewers comments are given in bold while our replies are written in regular roman letters. Citations from the revised manuscript are given as indented and italic text.

Detailed Replies

Corrections methods and their evaluation are thoroughly described for the shortwave and longwave. In addition, a comparison of the observations with radiative transfer calculations for the downwelling and upwelling shortwave radiative fluxes for horizontal, circular flight patterns has been presented. Such a comparison would be also highly valuable for the (downwelling) longwave in order to estimate the reliability of the longwave observations and to study potential effects which may become relevant in the longwave on such flights. For instance, the fraction of the direct solar beam above the cut-on of a pyrgeometer, which is at about 4.5 μ m for a CGR4. This unintentionally observed portion of the direct solar beam depends on the water vapor content (and thus altitude) and the solar zenith angle and hence may exceed 5 $\mathrm{W\,m^{-2}}$ significantly on such flights (e.g., Marty, 2000). In addition, the dependency of the pyrgeometer sensitivity on the water vapor content, which is estimated to be about 5 $\mathrm{W\,m^{-2}}$ in cloudfree conditions, may also be considered in such applications (e.g., Nyeki et al.,2017).

Thanks for this valuable suggestion! We did not simulated the thermal-infrared downward irradiance due to the higher sensitivity to the water vapor column above the aircraft and the distance to the radiosondes. That's why we did not expect to be able to identify this bias. We now run the simulations of downward thermal-infrared irradiance for the EUREC4A measurements with the best estimate of the atmosphere profile and compared to the measurements. Indeed, a slight positive bias of up to $10\,\mathrm{W\,m^{-2}}$ is observed when the downward solar radiation is high. In the revised manuscript, we included this analysis and discussed the offset.

In the abstract we added:

> *Special materials, e.g., quartz glass, silicon, as well as filter coatings guarantee a relatively constant sensitivity of the instrument over the desired spectral range (Groebner et al., 2007). However, unshaded pyrgeometer may suffer from leakage effects when solar radiation is transmitted above the cut-on wavelength of the pyrgeometer dome interference filter (Marty 2000; Meloni et al., 2012).*

The new section reads:

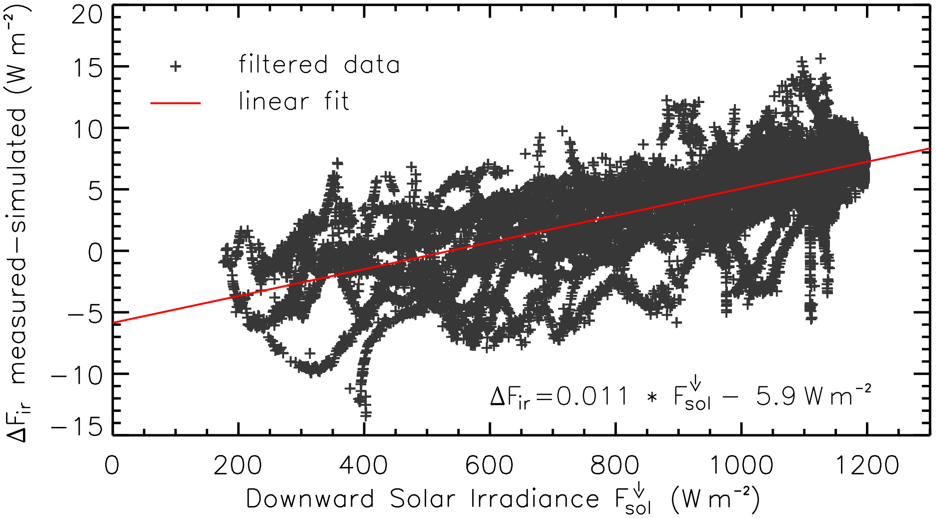

Figure 1. Difference between measured and simulated downward thermal-infrared irradiance $\Delta F_{\mathrm{ir}}^{\downarrow}$ for 12 EUREC^{4}A flights filtered for cloud-free conditions and flight altitudes above 10 km. The differences are plotted and fitted as function of the measured downward solar irradiance $F_{\mathrm{sol}}^{\downarrow}$.

> *The HALO flights of EUREC^{4}A have mostly been performed at flight altitudes above 10 km and under often cloud-free conditions above HALO, causing high values of downward solar irradiance. In such conditions the solar leakage of the pyrgeometer dome interference filter can produce an overestimation of the thermal-infrared irradiance (Philipona et al., 1995; Marty, 2000; Meloni et al., 2012). For cloud-free ground-based measurements, Meloni et al. (2012) identified an overstimation of up to 10* $\mathrm{W\,m^{-2}}$ *depending on the amount of downward solar irradiance.*

> *This bias was investigated for BACARDI using radiative transfer simulations of $F_{\mathrm{ir}}^{\downarrow}$ which are reliable and can serve as a benchmark for measurement above 10 km and under cloud-free conditions. The simulations have been performed along the HALO track, considering the time of day, the geographical position, and flight altitude of HALO with a temporal resolution of at least 30 s. The radiative transfer solver DISORT 2.0 and the lowtran parameterization of molecular absorption embedded in libRadtran are applied (Emde et al., 2016; Stamnes et al., 2000; Ricchiazzi and Gautier, 1998). In the simulations, the cloud-free atmosphere is defined by merged temperature and humidity profiles from the Barbados Cloud Observatory radiosondes (BCO, Stevens et al., 2016; Stephan et al., 2021), and the frequent dropsonde measurements from HALO (George, 2021).*
> *Filtered for cloud-free condition, Figure 9 shows the difference between measured and simulated $F_{\mathrm{ir}}^{\downarrow}$ as function of the measured downward solar irradiance $F_{\mathrm{sol}}^{\downarrow}$. The data indicates a trend to overestimate $F_{\mathrm{ir}}^{\downarrow}$ for increasing $F_{\mathrm{sol}}^{\downarrow}$. For values of $F_{\mathrm{sol}}^{\downarrow}$ above 1000 $\mathrm{W\,m^{-2}}$, typical for times around solar noon, the bias ranges up to 10 $\mathrm{W\,m^{-2}}$ comparable to the findings of Meloni et al. (2012). A linear regression suggest an increase of the bias by 1 $\mathrm{W\,m^{-2}}$ for each 100 $\mathrm{W\,m^{-2}}$ increase of $F_{\mathrm{sol}}^{\downarrow}$. However, the data shows a large variability and the regression suggests a negative bias for the absence of solar radiation. This may be attributed to remaining uncertainties of the radiative transfer simulations and the pyrgeometer sensitivity due to changes of water vapor concentrations above HALO (Nyeki et al., 2017), a permanent biases of the radiometer calibration, and a static thermal offsets*

In the conclusions we added:

> *In conditions with high $F_{\mathrm{sol}}^{\downarrow}$, the pyrgeometer show a slight bias due to leakage of solar radiation above the cut-on wavelength of the CGR4 interferrence filter. This bias correlates with $F_{\mathrm{sol}}^{\downarrow}$ and amounts up to 10 $\mathrm{W\,m^{-2}}$ during solar noon.*

Would it possible to calculate an uncertainty budget for the BACARDI package or at least to give a conclusive uncertainty estimate for the individual components of the observed radiative fluxes and the net radiation?

As shown in the manuscript, the uncertainties the irradiances result from different sources and processes, which are partly compensated by the applied corrections. As the magnitude of the biases and the corrections depends on a number of parameters such as the change of ambient temperature, solar zenith angle, direct fraction of solar radiation, also the remaining uncertainties of the radiometer are not a constant value. It rather depends on the specific atmospheric conditions and flight pattern. In addition, such biases may be come more important for low values of irradiance while in contrast the uncertainty of the radiometer sensor sensitivity scales with the magnitude of the irradiance. Thus estimating a conclusive general uncertainty estimate is challenging. We rather leave it to the publication of specific applications of the data to sum up the individual sources of uncertainty discussed in the manuscript, e.g. for level flights in high altitude or profiles for deriving heating rates. To make it more clear, that despite all corrections, a major part of the uncertainty results from the radiometer sensitivities, we edited and added in the conclusion:

> *... for straight flight legs maintaining constant flight levels, which are more typical for HALO observations, the temperature changes are small (below 5 K per hour), and potential dynamic thermal offsets range below 1* $\mathrm{W\,m^{-2}}$ *for all broadband irradiances, which appears negligible compared to the uncertainties of the sensor sensitivities (*$1\,\%$ *for the CMP22 pyranometer and 4 % for the CGR4 pyrgeometer).*

It is indicated that the thermal offset correction coefficient β of the upper and lower pyrgeometer is more consistent compared to the upper and lower pyranometer due to the position of the pyrgeometers in front of the pyranometers with respect to the flight direction, which allows the pyrgeometers to be ventilated more effectively. Would it possible to place the pyranometer to the side of the pyrgeometers to further reduce thermal offsets or impedes the mounting system of BACARDI or limited space in the fuselage such a setup?

This is a valid suggestion. However, the aperture plates on which the radiometers are mounted have limited space and allow only a in line alignment of both radiometers. In addition due to other constrains such as the limited number of central apertured and certification costs, the construction of BACARDI is fixed for the near future.

Line 32: may use "... by radiometers, ... pyranometers ... pyrgeometers"

Thanks! We now tried to consistently use plural throughout the manuscript.

Line 55: may use "Actively stabilized pyranometers, ..."

Thanks! We now tried to consistently use plural throughout the manuscript.

Line 83: may use "The radiative energy budget of a broadband radiometer"

Thanks! We now tried to consistently use plural throughout the manuscript.

Lines 129/140: In my opinion, the sensitivity is normally given in units of V $\mathrm{W^{-1}\,m^{2}}$ (see line 189). Hence, the stated unit W $\mathrm{m^{-2}V^{-1}}$ refers to the reciprocal of the sensitivity à may use "... adjusted reciprocal of the pyrgeometer/pyranometer sensitivity..."

You are right, the sensitivity of a sensor is defined the inverse way. Our intention was to make the equations which refer to the irradiance easier to read. Using a term like "reciprocal of sensitivity" we think will produce even more confusion. So finally, we decided to change the equation to the proper definition of sensitivity in units of $\mathrm{V\,(W\,m^{-2})^{-1}}$.

Line 157: delete one "the"

Thanks!

Line 313: "... depends..."

Thanks!

Fig. 5: Is there an indication for the cause of the “outliers” in Fig. 5 (grey points)? Are these the same datapoints for the shortwave and longwave? May give a short statement in the text.

The gray points in the plot show all data from the night flight (1 1/2 hours). The colored crosses show data during ascents and descents that were used to the regression (1 hour for the pyranometers and four short 3-4 min sections for the pyrgeometers). The sections of the pyrgeometers were selected by hand, when a significant reaction of the thermophile signal occurred during ascents and descents. For the pyranometer the conditions were more stable. Only sections during start and landing needed to be removed from the regression. However, for the pyranometer, the slope at these data (gray symbols) branches is similar to the regression, only that for zero temperature change, still a bias would exist. Reasons for that we could not be identify. For the pyrgeometer the variabiltity of the removed data (gray symbols) illustrates the variability of thermal-infrared radiation due to changes of the atmosphere which are not fully removed by detrending the data. In the revised manuscript, we added some more explanation in the text and the figure caption:

> *Data measured shortly after start and before landing (gray symbols) were not used to determine the thermal offsets.*

> *Gray symbols show all data of the night flight on 15 May 2019 (about 1.5 hours)*

Line 346/347: I would replace “… a few W m-2” by “…to values below 10 $\mathrm{W\,m^{-2}}$” (as in the abstract). For the downwelling shortwave flux, values are rather between 5 and 10 $\mathrm{W\,m^{-2}}$ above 6 km but also partly near the surface. Only in the upwelling shortwave and in the downwelling shortwave up to 6 km values are a few $\mathrm{W\,m^{-2}}$

That is correct. We adjusted to the statement given in the abstract that the bias is reduced "to values below 10 $\mathrm{W\,m^{-2}}$.

Line 416: Delete either “the” or “a”

Thanks!

Line 432: I do not understand the expression “… false detection of clouds above the aircraft…”. May rephrase, e.g., “… caused by cloud contamination above the aircraft in the filtered dataset, …” or similar. Significant lower observed irradiances with respect to the calculated fluxes are either due to real clouds above the aircraft or a not properly corrected misalignment of the sensor.

Thanks for pointing at this unprecise expression. We changed the sentence in the revised manuscript:

> *This might be caused by a remaining contamination of the filtered data by clouds above the aircraft, which are not considered in the cloud-free simulations.*

Line 433: "… conditions of high solar zenith angles, …"

Thanks again!

Lines 413-456: I got a bit confused here: Fig. 9a is presented and described in lines 413-423. Then Fig. 10a and 10b are described in lines 424-448. Finally, you go back again to Fig. 9b in lines 449-456. It might be easier for the reader, if the description of Fig. 9b (lines 449-456) was placed right after the description of Fig. 9a in line 423. However, you may have good reasons not to do it.

When writing the manuscript, we also struggeled with the issue that downward and upward irradiance are shown in Fig. 9 but Fig. 10 additionally addresses the downward irradiance. Finally we decided to discuss first all analysis for the downward irradiance (including Fig. 10) and then coming back to the upward irradiance. We think not splitting up the discussion on the attitude correction of the downward irradiance is more important and keep the section as it is.