Authors' response to reviewer #2 comments on the manuscript:

"Evaluation of downward and upward solar irradiances simulated by the Integrated Forecasting System of ECMWF using airborne observations above Arctic low-level clouds" [EGUSPHERE-2023-2443]

We thank the anonymous referee for his/her time and for the helpful comments and suggestions, especially on a better description of how the sensitivity study was performed, which helped us to improve the manuscript. After repeating the reviewer's comments in black we detail our responses to each of these comments in blue below. The line numbers contained in the authors' response correspond to the revised version of the manuscript.

We have also taken the opportunity to

A) correct rounding errors of some differences between simulated and observed irradiance in the manuscript to reach consistency between the values indicated in the different figures, the tabular overview and the text passages, and

B) rename "LWC" to "LWP" in Fig. 7 and Fig. 8 to reach consistency within the manuscript.

The authors use ACLOUD field campaign data to quantify the representation and uncertainty of Arctic low-level clouds in the ECMWF Integrated Forecasting System (IFS). The model's horizontal resolution is 1.4 km to 7.8 km. It has 137 vertical levels. To focus on low-level clouds, the authors only use cases with clouds below the level of Polar 5 and no cloud above. The comparisons of IFS and observed downward and upward irradiance are presented statistically to avoid the error due to temporal and spatial mismatch. To quantify the sensitivity of cloud properties, cloud fraction, ice water path, liquid water path, and cloud particle number concentration, as well as surface albedo are perturbed. Then a off-line radiative transfer code is used to assess the impact on the upward irradiance. The authors find the sea ice spectral albedo is the largest contributor to the bias in the upward irradiance above sea ice.

The analysis demonstrates the utility of field campaign data to evaluate high resolution models. This paper can potentially become a high impact paper. However, the use of statistical analysis in identifying cloud properties that are responsible for the bias is limited. In the end, the authors only use mean differences to evaluate the contribution. In addition, how the sensitivity study was performed needs to be clarified.

Major issues

Equations 3 and 4 show relationship among cloud properties. When the liquid water path is perturbed by keeping the shape of vertical profile, the liquid water content is scaled by the ratio of liquid water paths. The scaling liquid water content affects effective radius, according to Equation 4. It is not clear to me, therefore, when LWP is perturbed, whether this is a partial derivative or other cloud properties change according to Equations 3 and 4. This probably affect the result of the number concentration perturbation most. The authors need to describe more to clarify how the sensitivity study was performed.

- The scaling of specific parameters for the sensitivity study is not performed via a partial derivative, but with subsequent changes of the liquid effective radius triggered by initial adjustments of LWC and cloud droplet number concentration according to Eq. 4. For LWC adjustment (Sect. 4.3.2), the cloud droplet number concentration remains fixed. For cloud droplet number concentration adjustment (Sect. 4.3.3), the LWC remains fixed. The scaling of

IWC (Sect. 4.3.1) is followed by a subsequent adjustment of the ice effective radius according to Sun and Rikus (1999) and Sun (2001). In each relevant subsection, we added adequate details to clarify how the sensitivity study was performed for the relevant parameter:

- Section 4.3.1: “This increase (reduction) of IWP is propagated to an increase (reduction) of the ice effective radius according to Sun and Rikus (1999) and Sun (2001).” (lines 332-333)
- Section 4.3.2 (observation based): “The liquid effective radius is recalculated respectively, considering the changed LWC in Eq. 4. After adjusting, r_{eff} is limited to 4-30 µm to match the IFS constraints again. N_{d} remains fixed.” (lines 362-364)
- Section 4.3.2 (non-observation based): “[…] going along with the according increase and decrease of r_{eff}. N_{d} remains fixed.” (lines 374-375)
- Section 4.3.3: “The liquid effective radius is recalculated respectively, considering the changed N_{d} in Eq. 4, while LWC remains fixed.” (lines 413-414)

The authors show distributions of irradiances in Figures. Also, Hellinger distances were computed. However, the authors do not discuss distribution differences. I would like to see discussions of distribution differences and how the distribution differences are used to narrow the uncertainty to identify cloud properties contributing the bias of upward irradiances.

➢ While Section 3 covers a discussion of multiple differences between various distributions in Fig. 2, we added some missing discussion of distribution differences and how they contributed to $\Delta F^{\uparrow}$ throughout the whole Section 4:
  - Section 4.1 now contains “In comparison to the reference distribution, the adjusted distribution emerges with 320 W m^{-2} at a 10 W m^{-2} higher upward irradiance, but ends 20 W m^{-2} higher at 470 W m^{-2}. The distribution itself is shifted to higher values throughout all upward irradiances with the highest peak located between 420-430 W m^{-2}.” (lines 285-287)
  - Section 4.2 now contains: “Above open ocean, occurrences of upward solar irradiance between 200 W m^{-2}and 460 W m^{-2} are mainly lower compared to the reference distribution. This reduction enables a new mode occurring at very low upward irradiances between 40 W m^{-2} and 50 W m^{-2}. The replacement by the observed cloud fraction results in a higher amount of data with low reflected irradiances.” (lines 320-322)
  - Section 4.3.2 (observation based) now contains: “Compared to the reference distribution, the adjusted distribution emerges already at 80 W m^{-2} instead of 150 W m^{-2} and ends at upward irradiances 20 W m^{-2} lower than before. The main mode ranges between 230 W m^{-2} and 290 W m^{-2} instead of between 320 W m^{-2} and 340 W m^{-2}. Adjusting the LWP based on observations leads to a change in the correct direction by reducing the upward solar irradiances. Compared to the observations, this impact is too strong resulting in a conversion of the overestimation to an underestimation.” (lines 366-370)
  - Section 4.3.2 (non-observation based) now contains: “Above sea ice, the increase of the LWP and the implicit change of r_{eff} improves $\Delta F^{\uparrow}$ (Fig. 8a) by a slightly higher emergence of the upward irradiance distribution at 320 W m^{-2}, by slightly higher irradiances over a wide range of the distribution and by keeping the same end of the distribution as in the reference case. Above open ocean, the decrease of the LWP and the implied r_{eff} improves $\Delta F^{\uparrow}$ (Fig. 8b) by shifting the entire distribution to 20-30 W m^{-2} lower upward irradiances.” (lines 380-383)

- Section 4.3.3 now contains: “In general, the increase of N_d increases the reflected solar irradiance. Above sea ice, the maximum values of upward solar irradiance reach 460 W m^{-2} instead of 450 W m^{-2} while the minimum remains unchanged. In between, the distribution is shifted to slightly higher irradiances. Above open ocean, the entire distribution of adjusted upward solar irradiances is shifted to higher irradiances, with the minimum and maximum ranging 10 W m^{-2} higher.” (lines 414-418)

Minor issues

Figure 2: dotted lines used for open ocean make the plot hard to see. Could them change to solid lines? Also tick labels of x-axis for the upper plots are missing. Are these the same as upward irradiance? Also, including mean irradiance values to the upper left helps.

- We changed in Fig. 2 the dashed lines above open ocean to solid lines. The x-axes of the downward irradiances is shared with the x-axes of the upward irradiances. For clarification the (shared) tick labels are now repeated at the ticks of the two upper panels. As suggested, the mean irradiance values are displayed at the upper left of each panel.

Figure 3: Are IFS sea ice albedo climatologies indicated by the solid lines?

- Exactly, the IFS sea ice albedo climatology from Ebert and Curry (1993) is indicated by the solid lines, as mentioned in the legend of Fig. 3a. To clarify this, the descriptions “circles” and “solid lines” were added to the figure caption, which now reads:
  “Time series of modes of measured sea ice albedo in the 400-690 nm, 690-1190 nm and 1190-2155 nm band (circles) and IFS sea ice albedo climatology (solid lines). The dashed lines show the parameterization for the measurements. […]”

References

Ebert, E. E. and Curry, J. A.: An intermediate one-dimensional thermodynamic sea ice model for investigating ice-atmosphere interactions, J. Geophys. Res., 98, 10085, https://doi.org/10.1029/93JC00656, 1993.

Sun, Z.: Reply to comments by Greg M. McFarquhar on ‘Parametrization of effective sizes of cirrus-cloud particles and its verification against observations’. (October B, 1999,125, 3037–3055), Q.J Royal Met. Soc., 127, 267–271, https://doi.org/10.1002/qj.49712757116, available at: https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.49712757116, 2001.

Sun, Z. and Rikus, L.: Parametrization of effective sizes of cirrus-cloud particles and its verification against observations, Q.J.R. Meteorol. Soc., 125, 3037–3055, https://doi.org/10.1002/qj.49712556012, 1999.