Response to anonymous reviewer #1

We thank the reviewer for his/her positive judgement on the manuscript and the helpful comments, which we address in this revision. (1) We have provided more detailed explanations on distinguishing cloudy and clear-sky regions, the derivation and threshold of IWC in ERA5, and the relationship between RHi and temperature from both the ERA5 model and measurements. (2) We further explain for using CIRRUS-HL campaign measurements but no other data for model validations. To this end, we have included clear explanations regarding contrail formation threshold and satellite observation resolution.

In the following we enumerate the referee's comments (RC) and our replies (R) to each, referencing the corresponding tracked changes in the manuscript.

RC: Summary of paper:

Review of "Machine learning for improvement of upper tropospheric relative humidity in ERA5 weather model data", by Wang and coauthors, EGUSphere-2024-2012.

The goal of this study is to improve the estimations of the relative humidity with respect to ice in the upper troposphere/lower stratosphere from ERA5 fields using machine learning. To achieve this goal, the authors develop an artificial neural network model to correct relative humidity from ERA5, using thermodynamic conditions and dynamical quantities from ERA5, together with water vapor data from IAGOS commercial aircraft measurements. The model RHi is trained using these data. Overall, this is an excellent article, and, although I spent a lot of time thinking about different aspects of the model, I have relatively few comments.

Comments:

RC1: Line 64. You may want to mention that calibration of RH instruments at temperatures below 0° C are difficult, with increasing difficulty at decreasing temperatures.

R1a) author's response

Thanks for pointing out this aspect. We have included the suggested explanation of the RH instrument calibration issue, as their measurements are a key source for assimilation in NWP models.

R1b) manuscript changes

L65-66: "While as the primary data source for the assimilation system, calibrating RH instruments at temperatures below 0°C is challenging, with the difficulty increasing as temperatures drop further."

RC2: 145. A brief mention of how ciwc is derived from ERA5, as it is so important a variable to differentiate cloudy and cloud-free regions, would be helpful.

R2a): author's response

Thank you for your comment, which indeed warrants further explanation. Cloud fraction and cloud ice/water content in ERA5 are derived from the prognostic cloud scheme. The text has been revised, and the relevant references have been added.

R2b) manuscript changes

L151-153: “*ciwc* represents the mass of cloud ice particles per kilogram of moist air, averaged over a grid box. It is estimated using the prognostic equations of the cloud scheme (Tiedtke, 1993; Forbes and Tompkins, 2011; Forbes and Ahlgrimm, 2014), which account for cloud ice growth through deposition.”

References

Forbes, R. M. and Ahlgrimm, M.: On the representation of high-latitude boundary layer mixed-phase cloud in the ECMWF global model, Mon. Weather Rev., 142, 3425–3445, https://doi.org/10.1175/MWR-D-13-00325.1, 2014.

Forbes, R. and Tompkins, A.: An improved representation of cloud and precipitation, Tech. Rep., European Center for Medium-Range Weather Forecasting, https://doi.org/10.21957/nfgulzhe, 2011.

Tiedtke, M.: Representation of clouds in large-scale models, Mon. Weather Rev., 121, 3040–3061, https://doi.org/10.1175/1520-0493(1993)121<3040:ROCILS>2.0.CO;2, 1993.

RC3: 168. “accounts for” rather than “copes”

R3a): author’s response

Replaced “copes with” with “accounts for” in L177.

RC4: 189. At temperatures below -40° C, RHi should not exceed 100%, even though it may be above that value for a short period of time.

R4a) author’s response

Thank you for your question regarding data validity. As you pointed out, RHi can exceed 100% even when temperatures (T) are below -40 °C for some time, due to the ice supersaturation required for cirrus ice crystals formation and other non-equilibrium processes in the atmosphere. Long-term observations show that there is plenty of ice supersaturation in the upper troposphere, where T are usually colder than -40° C. Therefore, we think there is no need to constrain the measurement range to T above -40°, as we are also interested in the typical cirrus regime where T <-40°.

RC5: 202. contrail formation threshold. A sentence is needed here-how is the threshold met? The Schmidt-Appleman criteria?

R5a): author’s response

Thank you for your comment. Contrails form when hot, humid exhaust mixes with colder ambient air below the critical temperature known as the Schmidt-Appleman criterion. The text has been revised to explain how this threshold is reached, and the relevant references have been added.

R5b) manuscript changes

L211-212: “When the ambient temperatures fall below the Schmidt-Appleman criterion threshold (Schumann, 1996) at two successive flight waypoints” …

Reference

Schumann, U.: On conditions for contrail formation from aircraft exhausts, Meteorol. Z., 5, 4–23, https://doi.org/10.1127/metz/5/1996/4, 1996.

RC6: 217-218. What is the spatial resolution of the radiometer?

R6a) author's response

Thank you for pointing out this detail. SEVIRI provides observations with a 3 km sampling distance at nadir. The text has been revised accordingly.

RC7: Section 4. Model evaluation and results. An additional evaluation could be made by using collocated CALIPSO lidar data.

R7a) author's response

Thank you for suggesting this approach to evaluate the improved RHi data with lidar data. Unfortunately, CALIPSO lidar provides cirrus optical thickness and other properties based on backscatter measurements, but it does not provide humidity data. Humidity retrieval requires temperature profiles, which are typically derived from weather model data. While AIRS satellite observations include water vapor measurements, they have coarse spatial resolution in the vertical direction with large altitude bins. Therefore, we refrain from an additional evaluation using for instance CALIPSO lidar data.

RC8: Figure 5. You get cloudy skies from ERA5 when IWC is indicated? How accurate is this?

R8a) author's response

Thank you for your questions. In this study, we use ice water content (IWC) to differentiate between cirrus clouds and cirrus-free regions within the ERA5 grid. For the IWC detection threshold, we reviewed the literature and found that while a threshold of 0.1 g/m³ is commonly used (e.g., Krämer et al., 2020), lower IWC values are also observed in cirrus cloud regions (see Table 1 in Hong and Liu, 2015). Therefore, we use a valid IWC (>0) as an indicator for cirrus cloud regions and acknowledge that different IWC thresholds could be applied for finer cirrus classifications, as discussed in the literature.

Since this analysis relies on ERA5 data, it reflects model cloudiness rather than direct observations. We chose ERA5 IWC data because ERA5 include all necessary input quantities of our ANN models, such as RHi and atmospheric physics parameters. Although potential discrepancies between model and real clouds may exist, this approach agrees with the scope of our current research, and the mismatch can be further explored in future studies.

R8b) manuscript changes

L183-184: hence we differentiate between "model" clear (cloudy) conditions using *ciwc* equal to zero for all the current and ±2 pressure layers from ERA5…

Reference

Hong, Y. and Liu, G.: The characteristics of ice cloud properties derived from CloudSat and CALIPSO measurements, J. Climate, 28, 3880–3901, https://doi.org/10.1175/JCLI-D-14-00666.1, 2015.

Krämer, M., Rolf, C., Spelten, N., Afchine, A., Fahey, D., Jensen, E., Khaykin, S., Kuhn, T., Lawson, P., Lykov, A., Pan, L. L., Riese, M., Rollins, A., Stroh, F., Thornberry, T., Wolf, V., Woods, S., Spichtinger, P., Quaas, J., and Sourdeval, O.: A microphysics guide to cirrus – Part 2: Climatologies of clouds and humidity from observations, Atmos. Chem. Phys., 20, 12569–12608, https://doi.org/10.5194/acp-20-12569-2020, 2020.

RC9: Figures 4, 5, 6. Could you possibly partition by 5° C increments in supplemental information to see if RHi>100% at temperatures below -40° C, because it shouldn't.

R9a) author's response

Thank you for your suggestions. The response provided here is the same as the one given to RC4.

RC10: 408. You may want to mention that ECLIF3 was an experiment involving synthetic aviation fuel. The DLR Falcon jet research aircraft participated in the project, making some measurements simultaneously with the A350 aircraft. Could you use the ANN model in these situations as a test of the model?

R10a) author's response

Thank you for highlighting this potential comparison. In Figure S6 of the supplement, we present RHi derived from ERA5 and the ANN model, along with the differences relative to AIMS measurement obtained from the HALO aircraft on July 21, 2021, during the CIRRUS-HL campaign. The CIRRUS-HL experiment involved the HALO research aircraft, satellites, and models to provide new insights into the effects of aviation on clouds and the climate impact of contrails over Central Europe and the North Atlantic flight corridor. These aircraft measurements are extensively used for model validation related to water vapor and are also utilized to improve humidity assimilation in weather forecasting models. I agree with your point that ECLIF3 focuses on measurements related to sustainable aviation fuel, which is somehow beyond the scope of model validation in this context.