Response to Reviewer 2’ Comments

Review of “Characterizing the near-global cloud vertical structures over land using high-resolution radiosonde measurements” by Xu et al., for publication in EGUsphere

General Comments

The main point of this manuscript examines cloud vertical structure using radiosonde data from 374 land stations. Millimeter wavelength radar estimated cloud boundaries have a high correlation to radiosondes relative to ERA-5 derived cloud vertical structure, which is unsurprising. This study analyzes multi-layer clouds, with their analysis noting several instances of 3 or more cloud layers measured by a single radiosonde. This study is packed with interesting information about global cloud statistics, particularly how they vary in different regions of the world and for liquid, mixed and ice phase clouds. Their results discussing seasonal cloud boundaries are in very good agreement with several previous studies also using radiosondes for cloud property measurements. The figures are very high quality and complement the text very well.

There are few areas where this manuscript needs improvement. First, there is very little discussion about the radiosonde types or any discussion of measurement calibration/uncertainty. This is extremely important given the volume of radiosondes and noting that different versions (e.g., the Vaisala RS41 and RS92) were developed differently. The Vaisala RS92 in particular is prone to an RH dry bias, and there is no mention if those sondes (if they were used at all) employed any sort of correction or homogenization to the global database (aside from what we know about the GRUAN database). The authors need to make these points much more clear and do a better job of convincing the reader that the measurements are indeed homogenized. I think this can be accomplished in 1-2 additional paragraphs in the methods section, along with a table highlighting manufacturer/temperature/humidity (etc.) uncertainty and accuracy, along with documented studies noting any biases. Second, I think the authors missed a fantastic opportunity to explore their results in the context of relative humidity with respect to ice or RH(ice). RH(ice) is key for ice cloud formation, and though there are many studies that caution against the use of radiosonde relative humidity especially at high altitudes, the statistics of RH(ice) would be interesting to present nonetheless as it would give clear indication which climates around the world are most conducive to ice supersaturation. If the authors choose to add this to the paper, they will need to also ensure the uncertainty is well documented. In addition, there are several technical, grammatical and spelling errors in this manuscript that – while not significant in volume – was distracting and made the paper hard to read at times. I encourage the readers to carefully check their work for these errors.

Overall, this paper is a very extensive analysis of global cloud coverage that fits well within the scope of EGUsphere, and should be considered for publication after addressing several comments below.

Response: We thank the reviewer for his/her comprehensive evaluation and thoughtful comments, which help tremendously to improve the quality of our work. We have tried our best to address the reviewer' concerns one by one. For clarity purpose, here we have listed the reviewer' comments in black, followed by our responses in blue, and the modifications to the manuscript are in italics. We sincerely hope that the reply and the revisions can satisfy the editor and referee' expectations.

Specific Comments

1.L17: It would be good to elaborate a bit here in the abstract where these 374 land stations are partitioned.

Response: Thanks to your good suggestion, we changed the sentence " In this research, near-global CVS is characterized by high-vertical-resolution twice daily radiosonde observations from 374 stations over land." to "In this study, near-global CVS is characterized by high-vertical-resolution twice daily radiosonde observations from 374 stations over land, *which distributed in Europe, North America, East Asia, Austria, Pacific Ocean, and Antarctica*." in the revised version (Manuscript_tracked.docx).

2. L37-48: This is a solid introductory motivation.

Response: Thank you very much for your recognition.

3. L57: This is a bit awkwardly written. Perhaps consider moving the Hahn et al. (2001) reference to the end of the sentence.

Response: As suggested, the sentence was revised as "Ground-based instruments, such as lidars (Gouveia et al., 2017), ceilometers (Costa-Surós et al., 2013), and cloud radars (Mace et al., 1998), have proven to be effective in providing CVS with continuous temporal coverage and relatively high accuracy (*Hahn et al., 2001*; Zhou et al., 2020)." in the revised version (Manuscript_tracked.docx).

4. L57-61: I would be careful making the assertion that coverage of these ground-based radars/lidars/ceilometers are limited to "a few locations". You should expand this paragraph by at least 2-3 sentences and highlight where these locations are, and demonstrate to the reader that these measurements are indeed few. Otherwise, it undermines (in my opinion) a big part of the motivation of this research. The Atmospheric Radiation Measurement (ARM) program has many of these sites listed and available, and are definitely more than a few.

North Slope Alaska:

Zhang, D., Wang, Z., Luo, T., Yin, Y., and Flynn, C., 2017: The occurrence of ice production in slightly supercooled Arctic stratiform clouds as observed by ground-based remote sensors at the ARM NSA site, J. Geophys. Res. Atmos., 122, 2867– 2877, doi:10.1002/2016JD026226.

Tropical Western Pacific (note there were 3 sites):

Comstock, J. M., Protat, A., McFarlane, S. A., Delanoë, J., and Deng, M., 2013: Assessment of uncertainty in cloud radiative effects and heating rates through retrieval algorithm differences: Analysis using 3 years of ARM data at Darwin, Australia, J. Geophys. Res. Atmos., 118, 4549–4571, doi:10.1002/jgrd.50404.

Eastern North Atlantic:

Giangrande, S. E., Wang, D., Bartholomew, M. J., Jensen, M. P., Mechem, D. B., Hardin, J. C., & Wood, R. (2019). Midlatitude oceanic cloud and precipitation properties as sampled by the ARM Eastern North Atlantic Observatory. Journal of Geophysical Research: Atmospheres, 124, 4741– 4760. https://doi.org/10.1029/2018JD029667.

Southern Great Plains Site:

Dong, X., Minnis, P., Xi, B., Sun-Mack, S., and Chen, Y., 2008: Comparison of CERES-MODIS stratus cloud properties with ground-based measurements at the DOE ARM Southern Great Plains site, J. Geophys. Res., 113, D03204, doi:10.1029/2007JD008438.

Response: Thanks for your reminder. Additional text was added in the revised version (Manuscript_tracked.docx) as follows:

"The US Department of Energy's Atmospheric Radiation Measurement Program (ARM) Climate Research Facility (http://www.arm.gov) provides ground-based radar and lidar observations at fixed field sites: North Slope of Alaska (NSA; Zhang et al., 2017), Southern Great Plains (SGP; Dong et al., 2008), Tropical Western Pacific (TWP; Comstock et al., 2013), and Eastern North Atlantic (ENA; Giangrande et al., 2019), and several mobile field sites (Cadeddu et al., 2013). These measurements provide information on the vertical structure of clouds (Stokes and Schwartz, 1994; Ackerman and Stokes, 2003), and have been widely used to study the cloud properties on global climate (Mace and Benson, 2008; Chandra et al., 2015). However, the global coverage of these instruments is too sparse and limited."

References:

Ackerman, T. P., and Stokes, G. M.: The atmospheric radiation measurement program, Phys. Today., 56, 38–44, https://doi.org/10.1063/1.1554135, 2003.

Cadeddu, M. P., Liljegren, J. C., and Turner, D. D.: The Atmospheric radiation measurement (ARM) program network of microwave radiometers: instrumentation, data, and retrievals, Atmos. Meas. Tech., 6, 2359–2372, https://doi.org/10.5194/amt-6-2359-2013, 2013.

Chandra, A. S., Zhang, C. D., Klein, S. A., and Ma, H. Y.: Low-cloud characteristics over the tropical western Pacific from ARM observations and CAM5 simulations, J. Geophys. Res.-Atmos., 120, 8953–8970, https://doi.org/10.1002/2015JD023369, 2015.

Comstock, J. M., Protat, A., McFarlane, S. A., Delanoë, J., and Deng, M.: Assessment of uncertainty in cloud radiative effects and heating rates through retrieval algorithm differences: Analysis using 3 years of ARM data at Darwin, Australia,

J. Geophys. Res.-Atmos., 118, 4549–4571, https://doi.org/10.1002/jgrd.50404, 2013.

Dong, X., Minnis, P., Xi, B., Sun-Mack, S., and Chen, Y.: Comparison of CERES-MODIS stratus cloud properties with ground-based measurements at the DOE ARM Southern Great Plains site, J. Geophys. Res.-Atmos., 113, D03204, https://doi.org/10.1029/2007JD008438, 2008.

Giangrande, S. E., Wang, D., Bartholomew, M. J., Jensen, M. P., Mechem, D. B., Hardin, J. C., and Wood, R.: Midlatitude oceanic cloud and precipitation properties as sampled by the ARM Eastern North Atlantic Observatory, J. Geophys. Res.-Atmos., 124, 4741– 4760, https://doi.org/10.1029/2018JD029667, 2019.

Mace, G. G., and Benson, S.: The vertical structure of cloud occurrence and radiative forcing at the SGP ARM site as revealed by 8 years of continuous data, J. Clim., 21, 2591–2610, https://doi.org/10.1175/2007JCLI1987.1, 2008.

Stokes, G. M., and Schwartz, S. E.: The atmospheric radiation measurement (ARM) program: Programmatic background and design of the cloud and radiation test bed, Bull. Amer. Meteor. Soc., 75, 1202–1221, https://doi.org/10.1175/1520-0477(1994)075<1201:TARMPP>2.0.CO;2, 1994.

Zhang, D., Wang, Z., Luo, T., Yin, Y., and Flynn, C.: The occurrence of ice production in slightly supercooled Arctic stratiform clouds as observed by ground-based remote sensors at the ARM NSA site, J. Geophys. Res.-Atmos., 122, 2867–2877, https://doi.org/10.1002/2016JD026226, 2017.

5. L72-76: You should review the “cirrus cloud detection algorithm” subsection in Dzambo and Turner (2016) as their method provided a viable radiosonde/ground-based radar/lidar collocation algorithm. Their method was by no means perfect, but their method established both spatial and temporal restrictions to ensure a radiosonde was indeed launched into a cloud.

Dzambo, A. M., and Turner, D. D. (2016), Characterizing relative humidity with respect to ice in midlatitude cirrus clouds as a function of atmospheric state, J. Geophys. Res. Atmos., 121, 12,253– 12,269, doi:10.1002/2015JD024643.

Also consider the role of their “lag time” correction, which is also in this section.

Response: As suggested, we added the sentence “*Dzambo and Turner (2016) identified cirrus based on a cirrus cloud detection algorithm by using radiosonde and cloud radar data and found that RH with respect to ice within cirrus clouds varied seasonally, with maximum in winter and minimum in summer. To ensure the radiosonde measurements were collocated with the appropriate MMCR measurements, they established temporal (“lag time”) and spatial restrictions.*”

References:

Dzambo, A. M., and Turner, D. D.: Characterizing relative humidity with respect to ice in midlatitude cirrus clouds as a function of atmospheric state, J. Geophys. Res.-Atmos., 121, 12253–12269, https://doi.org/10.1002/2015JD024643, 2016.

6. L82: Where in the world are these 374 land stations? A few examples would be good to note here for the reader.

Response: As suggested, we added "*(e.g., Europe, North America, East Asia, Austria, Pacific Ocean, and Antarctica)*" to the sentence "The main objective of present study is to provide the first attempt to retrieve near-global vertical structures of clouds, including the number of cloud layers, cloud base height (CBH), cloud top height (CTH), and cloud thickness (CT) of each layer, using two years' worth (2018–2019) of high-vertical-resolution (5–10 m) radiosonde observations from 374 radiosonde stations across the world *(e.g., Europe, North America, East Asia, Austria, Pacific Ocean, and Antarctica)*."

7. L90: technical correction: "... we also investigate the relationship between CBH, surface meteorology, and moisture."
Response: Corrected as suggested.

8. Section beginning at L95: There is a very important piece of information missing from this section... the manufacturing information of all radiosondes used in your database. Were these radiosondes Vaisala RS-92? Vaisala RS-41? Because your results are very sensitive to the relative humidity measurements of the radiosonde, it is also necessary to know what humidity sensors are on each radiosonde, and by extension, it is further necessary to know and understand the relative humidity uncertainty with each. There are numerous studies discussing the topic about relative humidity corrections in radiosondes. Vaisala RS-92 radiosondes have a very well documented dry bias in their measurements, and to the extent of my knowledge, only the GRUAN database of radiosondes have their humidity products homogenized between different versions. I strongly recommend updating this section of the paper with at least a paragraph discussing the humidity measurements, as well as adding a table of the different sensors from each manufacturer, perhaps something like: manufacturer, years used, reference for sensor, instrument uncertainty, and (if applicable) known biases and corrections such as those for the RS-92.

Wang, J., L. Zhang, A. Dai, F. Immler, M. Sommer, and H. Vömel, 2013: Radiation Dry Bias Correction of Vaisala RS92 Humidity Data and Its Impacts on Historical Radiosonde Data. J. Atmos. Oceanic Technol., 30, 197–214, https://doi.org/10.1175/JTECH-D-12-00113.1.

Miloshevich, L. M., Vömel, H., Whiteman, D. N., and Leblanc, T. (2009), Accuracy assessment and correction of Vaisala RS92 radiosonde water vapor measurements, J. Geophys. Res., 114, D11305, doi:10.1029/2008JD011565.

Vömel, H., and Coauthors, 2007: Radiation Dry Bias of the Vaisala RS92 Humidity Sensor. J. Atmos. Oceanic Technol., 24, 953–963, https://doi.org/10.1175/JTECH2019.1.

Dzambo, A. M., Turner, D. D., and Mlawer, E. J.: Evaluation of two Vaisala RS92 radiosonde solar radiative dry bias correction algorithms, Atmos. Meas. Tech., 9, 1613–1626, https://doi.org/10.5194/amt-9-1613-2016, 2016.

Jensen, M. P., Holdridge, D. J., Survo, P., Lehtinen, R., Baxter, S., Toto, T., and Johnson, K. L.: Comparison of Vaisala radiosondes RS41 and RS92 at the ARM

Southern Great Plains site, Atmos. Meas. Tech., 9, 3115–3129, https://doi.org/10.5194/amt-9-3115-2016, 2016.

de Boer, G., Calmer, R., Jozef, G. et al. Observing the Central Arctic Atmosphere and Surface with University of Colorado uncrewed aircraft systems. Sci Data 9, 439 (2022). https://doi.org/10.1038/s41597-022-01526-9 (see methods section of this paper)

These are papers that should provide good context for RS41 and RS92 humidity measurements. As for the other radiosondes that may have been used in your study, please search for and add documentation similar to what these studies have in addressing humidity measurements.

Response: As suggested, we added the additional text as follows:

"The *Vaisala RS92 radiosonde is widely used by NOAA, the German Deutscher Wetterdienst, the CEDA, and the University of Wyoming. The Vaisala RS92 humidity sensor measures RH every 2 s (Wang et al., 2018), and its uncertainty is 5 % RH (Jauhiainen and Lehmuskero, 2005). Due to solar radiation heating, the RH data results in a dry bias in the upper troposphere (Vömel et al. 2007). Several correction algorithms have been developed to correct the solar radiation dry bias (e.g., Vömel et al., 2007; Cady-Pereira et al., 2008; Yoneyama et al., 2008; Miloshevich et al., 2009; Wang et al., 2013). The Vaisala RS41 radiosonde is used in the stations of GRUAN. Since temperature of the humidity sensor can be measured by the temperature sensor and taken into account in the RH calculation, no separate solar radiation dry bias correction is needed for the RS41 humidity measurement (Jensen et al., 2016). The RS41 humidity sensor has an uncertainty of 3 % RH (Vaisala, 2017). The GTS1 digital radiosonde is used by CMA, having the advantages of high sensitivity, quick sampling, and small volume (Li, 2006; Bian et al., 2011; Chen et al., 2021). The humidity sensor of GTS1 samples RH at a time interval of approximately 1 s, with the uncertainty about 5 % RH (Li et al., 2009). The specifications for the Vaisala RS92, Vaisala RS41, and GTS1 digital radiosonde are shown in Table 1.*"

Table 1. The specifications of the Vaisala RS92, Vaisala RS41, and GST1 digital radiosonde.

Radiosonde characteristics	Vaisala RS92	Vaisala RS41	GTS1 digital radiosonde
Manufacturer	Vaisala Oyj, Finland	Vaisala Oyj, Finland	Shanghai Changwang Meteorological Science and Technology Company, China
Service period	2003 to date	2013 to date	2002 to date
Humidity sensor	Thin-film capacitor, heated twin HUMICAPS	Thin-film capacitor, integrated temperature sensor and heating functionality	Carbon-film hygristor
RH range	0 % to 100 %	0 % to 100 %	0 % to 100 %
RH uncertainty	5 % RH	3 % RH	~5 % RH
Dry bias corrections	Empirical mean bias correction algorithm (Miloshevich et al., 2009); NCAR radiation bias correction algorithm (Wang et al., 2013)	No separate solar radiation correction is needed	Humidity error correction based on fluid dynamic (Mao et al., 2016); PSO-BP neural network correction (Shan et al., 2018)
Vertical resolution	2 s	2 s	1 s
References	Jauhiainen and Lehmuskero, 2005; Vömel et al., 2007; Miloshevich et al., 2009; Wang et al., 2013	Jensen et al., 2016; Vaisala, 2017	Li, 2006; Li et al., 2009; Bian et al., 2011; Chen et al., 2021;

References:

Bian, J. C., Chen, H. B., Vömel, H., Duan, Y. J., Xuan, Y. J., and Lü, D. R.: Intercomparison of humidity and temperature sensors: GTS1, Vaisala RS80, and CFH, Adv. Atmos. Sci., 28, 139–146, https://doi.org/10.1007/s00376-010-9170-8, 2011.

Cady-Pereira, K. E., Shephard, M. W., Turner, D. D., Mlawer, E. J., Clough, S. A., and Wagner, T. J.: Improved daytime column-integrated precipitable water vapor

from Vaisala radiosonde humidity sensors, J. Atmos. Oceanic Technol.,25, 873–883, https://doi.org/10.1175/2007JTECHA1027.1, 2008.

Chen, C., Song, X. Q., Wang, Z. J., Wang, W. Y., Wang, X. F., Zhuang, Q. F., Liu, X. Y., Li, H., Ma, K., Li, X., Pan, X., Zhang, F., Xue, B., and Yu, Y.: Observations of atmospheric aerosol and cloud using a polarized Micropulse Lidar in Xi'an, China, Atmosphere, 12, 796, https://doi.org/10.3390/atmos12060796, 2021.

Jauhiainen H., and Lehmuskero M.: Vaisala White Paper, Performance of the Vaisala radiosonde RS92-SGP and Vaisala DigiCORA sounding system MW31 in the WMO Mauritius radiosonde intercomparison, February 2005.

Jensen, M. P., Holdridge, D. J., Survo, P., Lehtinen, R., Baxter, S., Toto, T., and Johnson, K. L.: Comparison of Vaisala radiosondes RS41 and RS92 at the ARM Southern Great Plains site, Atmos. Meas. Tech., 9, 3115–3129, https://doi.org/10.5194/amt-9-3115-2016, 2016.

Li, F.: New Developments with Upper-air Sounding in China, Instruments and Observing Methods Report, No. 94, WMO/TD, No.1354. Geneva: WMO, 2006.

Li, W., Xing, Y., and Ma, S.: The analysis and comparison between GTS1 radiosonde made in China and RS92 radiosonde of Vaisala company, Meteorological Monthly (in Chinese), 35, 97–102, 2009.

Mao, X., Zhang, J., Xiao, S., Liu, Q., Chen, Y., Dai, W., and Yang, J.: Research on corrections of humidity measurements errors from GTS1 radiosonde based on fluid dynamic analysis, Chinese J. Geophys. (in Chinese), 59, 4791–4805, https://doi.org/10.6038/cjg20161237, 2016.

Miloshevich, L. M., Vomel, H., Whiteman, D. N., and Leblanc, T.: Accuracy assessment and correction of Vaisala RS92 radiosonde water vapor measurements, J. Geophys. Res., 114, D11305, https://doi.org/10.1029/2008JD011565, 2009.

Vaisala: Vaisala Radiosonde RS41-SGP. Ref. B211444EN-E © Vaisala, 2017.

Vömel, H., Selkirk, H., Miloshevich, L., Valverde-Canossa, J., Valdes, J., Kyro, E., Kivi, R., Stolz, W., Peng, G., and Diaz, J. A.: Radiation dry bias of the Vaisala RS92 humidity sensor, J. Atmos. Oceanic Technol., 24, 953–963, https://doi.org/10.1175/JTECH2019.1, 2007.

Wang, J. H., Zhang, L. Y., Dai, A. G., Immler, F., Sommer, M., and Vömel, H.: Radiation dry bias correction of Vaisala RS92 humidity data and its impacts on historical radiosonde data, J. Atmos., Ocean. Tech., 30, 197–214, https://doi.org/10.1175/JTECH-D-12-00113.1, 2013.

Wang, Y. J., Xu, X. D., Zhao, Y., and Wang, M. Z.: Variation characteristics of the planetary boundary layer height and its relationship with PM2.5 concentration over China, J. Trop. Meteorol., 24, 385–394, https://doi.org/10.16555/j.1006-8775.2018.03.011, 2018.

Yoneyama, K., Fujita, M., Sato, N., Fujiwara, M., Inai, Y., and Hasebe, F.: Correction for radiation dry bias found in RS92 radiosonde data during the MISMO field experiment, SOLA, 4, 13–16, https://doi.org/10.2151/sola.2008-004, 2008.

Shan, P., Mao, X., Zhang, J., Ma, T., and Chen, Y.: Correction of solar radiation dry bias of radiosonde humidity based on PSO-BP neural network, Science Technology and Engineering (in Chinese), 18, 1–8, 2018.

9. L125: The comment here about the ERA-Interim is unnecessary.

Response: We deleted "Compared with former ERA-Interim" and revised the sentence as follows:

"The temporal and spatial resolutions of ERA5 can reach up to 1 hour (h) and 0.25° × 0.25°, respectively (Hersbach et al., 2020)."

10. L130: The inclusion of soil moisture content as part of your analysis is interesting, but can you provide context (perhaps a reference or two) showing how this ERA-5 variable was used in previous studies (especially for surface latent fluxes, clouds, or something similar).

Response: As suggested, we added these sentences "*As a key variable that links land surface to cloud formation, soil moisture from the ERA5 reanalysis has been widely used in the analysis of land-atmosphere coupling (Sun et al., 2020). By using the ERA5 reanalysis in East Asia, Wei et al. (2021) explored the relationships between soil moisture, land surface sensible and latent heat fluxes, and CBH, and found the negative correlations between soil moisture and CBH.*"

References:

Wei, J. F., Zhao, J. W., Chen, H. S., and Liang, X. Z.: Coupling between land surface fluxes and lifting condensation level: mechanisms and sensitivity to model physics parameterizations, J. Geophys. Res.-Atmos., 126, e2020JD034313, https://doi.org/10.1029/2020JD034313, 2021.

Sun, G. H., Hu, Z. Y., Ma, Y. M., Xie, Z. P., Yang, S., and Wang, J. M.: Analysis of local land-atmosphere coupling in rainy season over a typical underlying surface in Tibetan Plateau based on field measurements and ERA5, Atmos. Res., 243, 105025, https://doi.org/10.1016/j.atmosres.2020.105025, 2020.

11. L143: I am not convinced this is the best version of RH with respect to ice to use. Murphy and Koop (2005) did an extensive review of the available RH(ice) equations, pointing out an error (at the time) in the World Meteorological Organization's primary equation. Review this paper, and at minimum, comment on how this choice of equation might vary from the other formulations listed here. Goff and Gratch (1946) is very commonly used.

Murphy, D.M. and Koop, T. (2005), Review of the vapour pressures of ice and supercooled water for atmospheric applications. Q.J.R. Meteorol. Soc., 131: 1539-1565. https://doi.org/10.1256/qj.04.94.

Response: Thanks for your great suggestions. To quantify the difference between the formulation of saturation vapor pressure in the pure ice phase (e_{ice}) used in our study and other formulations from Murphy and Koop (2005), we added the sentences as follows:

"Note that besides equation (3), there are also several formulations for e_{ice} *(Murphy and Koop, 2005). In order to quantify the difference in* e_{ice}*, we also calculate the* e_{ice} *for -40 to 0 °C using several equations listed in Murphy and Koop (2005), which are proposed by Goff and Gratch (1946), Hyland and Wexler (1983), Sonntag (1990), and Marti and Mauersberger (1993). Obviously that the* e_{ice} *calculated using different formulations are nearly the same (Figure S1). Specifically,* e_{ice} *calculated by Murray (1967) is mostly closed to that by Goff and Gratch (1946), with the absolute difference less than 0.004 hPa, followed by Hyland and Wexler (1983) and Sonntag*

(1990), with the absolute difference less than 0.009 hPa. The largest differences in e_{ice} *exist between Murray (1967) and Marti and Mauersberger (1993), reaching up to 0.012 hPa. These results could prove that our choice for* e_{ice} *calculation is expected to affect the CVS results slightly."*

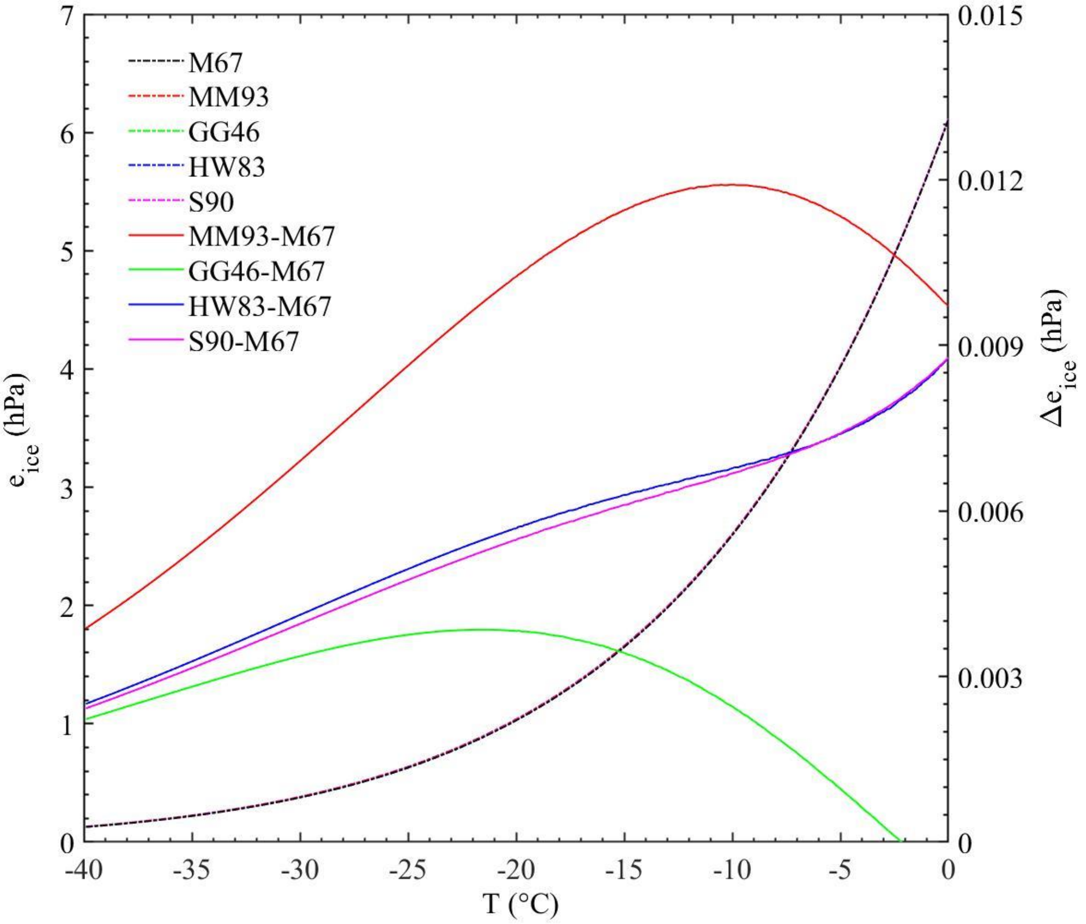

Figure S1. *The saturation vapor pressure in the pure ice phase* (e_{ice}) *for – 40 to 0 °C calculated by the expression in Murray (1967) (M76), Marti and Mauersberger (1993) (MM93), Goff and Gratch (1946) (GG46), Hyland and Wexler (1983) (HW83), and Sonntag (1990) (S90). Also shown is the absolute difference in* e_{ice} *between M76 with MM93, GG46, HW83, and S90, respectively.*

References:

Murphy, D. M., and Koop, T.: Review of the vapour pressures of ice and supercooled water for atmospheric applications, Q. J. Roy. Meteor. Soc., 131, 1539–1565, https://doi.org/10.1256/qj.04.94, 2005.

Goff, J. A., and Gratch, S.: Low-pressure properties of water from −160 to 212 F, in Trans. Am. Soc. Heating Air-Cond. Eng., 52, 95–122, presented at the 52nd annual meeting of the American society of heating and ventilating engineers, New York, 1946.

Marti, J., and Mauersberger, K.: A survey and new measurements of ice vapor pressure at temperatures between 170 and 250 K, Geophys. Res. Lett., 20, 363–366, https://doi.org/10.1029/93GL00105, 1993.

Hyland, R. W., and Wexler, A.: Formulations for the thermodynamic properties of the saturated phases of H2O from 173.15 K to 473.15 K, ASHRAE Trans., 89, 500–519, https://doi.org/10.1061/(ASCE)0733-9364(1984)110:4(533), 1983.

Sonntag, D.: Important new values of the physical constants of 1986, vapour pressure formulations based on the ITS-90, and psychrometer formulae, Z. Meteorol., 40, 340–344, 1990.

12. L191: Do you mean to say “Otherwise, this layer is discarded from the analysis”?
Response: Yes, we changed the sentence “Otherwise, the layer of moist is discarded.” to “*Otherwise, the moist layer is discarded from the analysis*.

13. L192: I already mentioned this once, but it might be worthwhile referring to Dzambo and Turner (2016) and using their time-lag correction for collocating radiosonde and ground-based radar measurements. With merged clouds, I don’t think it would change your result much given the correlation is quite high already.
Response: Thanks for your great suggestions. Actually, in the comparisons between the cloud base and top heights obtained by radiosonde with those from Ka-band millimeter-wave cloud radar (MMCR), we have already used the time lag correction for collocating radiosonde and MMCR measurements.

Additional text was added to illustrate this procedure, as follows:

“*Note that to collocate radiosonde-derived CBHs (CTHs) with appropriate MMCR measured CBHs (CTHs), the time lag correction proposed by Dzambo and Turner (2016) is used.*”

14. L192 (technical correction): Just say “To obtain robust cloud structures, …"
Response: Corrected as suggested.

15. L223: I would say “accurately” over “correctly”, since both instruments are limited in attaining truly “correct” measurements.
Response: As suggested, we changed “correctly” to “*accurately and reasonably*”.

16. L225: Do you mean R^2 values?
Response: Here, we mean correlation coefficient (R) values. We defined correlation coefficient as R in the previous paragraph.

17. L228-230: This is inaccurate. ERA-5 assimilates geostationary satellite radiance measurements, which are used for a host of applications. Review Hersbach et al. (2020) more carefully, particularly the sections discussing satelltie radiance assimilation and the cloud parameterization schemes used to evolve clouds in their output.
Hersbach, H, Bell, B, Berrisford, P, et al. The ERA5 global reanalysis. Q J R Meteorol Soc. 2020; 146: 1999– 2049. https://doi.org/10.1002/qj.3803.
Response: Thanks for pointing out this mistake. The sentence is revised as follows:

“*The reason for that the correlation coefficient at 1200 UTC is more than twice as large as at 0000 UTC is complicated, which may be associated with the uncertainties* *of RH and T profiles, and the assimilation windows (within 12 h) for model constraint when producing hourly ERA5 data (Hersbach et al., 2020).*"

References:

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J.- N.: The ERA5 global reanalysis, Q. J. Roy. Meteor. Soc., 146, 1999–2049, https://doi.org/10.1002/qj.3803, 2020.

18. L238-240: I don't doubt these conclusions, however, discussing the cloud parameterization schemes used for ERA-5 would make these statements more convincing to the reader, because it would help explain why/how cloud base heights in ERA-5 were lower than CloudSat/CALIPSO. Also keep in mind that CloudSat has a blind zone below 750m (see the Stephens et al. Reference you already cited).

Response: As suggested, we added the sentence as follows:

"*The reason may be associated with issues of cloud parameterizations schemes used for ERA5. The CBH in ERA5 is detected using the cloud cover or cloud water mixing ratio threshold. When cloud cover is greater than 1 %, the height from ground is defined as CBH (Wang et al., 2022), which may lead to the underestimation of CBH in ERA5.*"

References:

Wang, R. J., Zhou, R. J., Yang, S. P., Li, R., Pu, I. P., Liu, K. Y., and Deng, Y.: A new algorithm for estimating low cloud-base height in southwest China, J. Appl. Meteorol. Clim., 61, 1179–1197, https://doi.org/10.1175/JAMC-D-21-0221.1, 2022.

19. L243-244: Is this true globally, or just the regions where the radiosonde data were available?

Response: Indeed, the results from our radiosonde data can just represent the regions where the radiosonde data are available. Since the radiosonde stations are distributed on several continents, it is expected that our results approximately represent the near-global results. Fortunately, our mean cloud fraction has good agreement with the result reported by Stubenrauch et al. (2013). Their results are based on satellite observations, which are capable of providing a continuous synoptic survey of the cloud fraction over the entire globe.

20. L336: Cloud bases above the tropopause are often the result of "overshooting tops" from deeply penetrating cumulonimbus (thunderstorms).

Homeyer, C. R., and M. R. Kumjian, 2015: Microphysical Characteristics of Overshooting Convection from Polarimetric Radar Observations. J. Atmos. Sci., 72, 870–891, https://doi.org/10.1175/JAS-D-13-0388.1.

Response: Thanks for providing this good suggestion. To elucidate the potential reason for cloud bases above the tropopause, we added the sentences as follows:

"*The conditions that cloud bases above the tropopause are often results of the overshooting tops from strong convective storms, such as deeply penetrating cumulonimbus and thunderstorms (Rosenfeld et al., 2007; Homeyer and Kumjian, 2015; Liu et al., 2021). Due to strong upward motion contained in the strong convective storms, the overshooting tops can reach as high as 19–20 km (Hassim et al., 2014).*"

Reference:

Hassim, M. E. E., Lane, T. P., and May, P. T.: Ground-based observations of overshooting convection during the Tropical Warm Pool-International Cloud Experiment, J. Geophys. Res.- Atmos., 119, 880–905, https://doi.org/10.1002/2013jd020673, 2014.

Homeyer, C. R., and Kumjian, M. R.: Microphysical characteristics of overshooting convection from polarimetric radar observations, J. Atmos. Sci., 72, 870–891, https://doi.org/10.1175/jas-d-13-0388.1, 2015.

Liu, F. F., Zhu, B. Y., Lu, G. P., and Ma, M.: Outbreak of negative narrow bipolar events in two mid-latitude thunderstorms featuring overshooting tops, Remote. Sens., 13, 5130, https://doi.org/10.3390/rs13245130, 2021.

Rosenfeld, D., Fromm, M., Trentmann, J., Luderer, G., Andreae, M. O., and Servranckx, R.: The Chisholm firestorm: observed microstructure, precipitation and lightning activity of a pyro-cumulonimbus, Atmos. Chem. Phys., 7, 645–659, https://doi.org/10.5194/acp-7-645-2007, 2007.

21. L349: You mean to say "East Asia". Please check your manuscript for technical, grammar and spelling errors, as I have noticed several to this point in the manuscript.

Response: Corrected as suggested. We double-checked the whole manuscript and corrected several other technical, grammar and spelling errors in the revised version (Manuscript_tracked.docx).

22. L353-355: I agree with this conclusion.

Response: Thanks.

23. L386: "cloud base for clouds..."

Response: Thanks for your reminder. The sentence was revised as "Few studies provided the global spatial distribution of the occurrence frequencies of *clouds* with various number of layers (*from one- to five-layer*) by radiosonde measurements as shown in Figure 12."

24. L389-390: This is a good result, and consistent with many previous studies.

Response: Thanks.

25. L398-399: This is because the western US is often dry near the surface, hence boundary layer heights tend to be much deeper. I would add this information to this part of the text.

Response: Thanks for your great suggestion. We added this sentence "*This can be explained that the western USA is often dry near the surface, thus PBLHs tend to be much deeper, resulting in higher CBHs compared to eastern USA.*"

26. L416: I agree.

Response: Thanks.

27. L420-450: Referring to my previous comments about RH(ice), it would be good to note layers where RH(ice) exceeds 100%. Several studies note the presence of "subvisible" cirrus, which to this point your study does not mention. Subvisible cirrus are typically contained to the tropics, and worth elaborating here in perhaps 1-2 sentences. Additionally, analyzing RH(ice) would add very scientifically interesting detail to your study by identifying which climates have the most frequent ice saturation observations, which is extremely important for ice cloud formation.

Response: Thanks for your remainder. In the Section 3.5 Diurnal variation of cloud occurrence frequency with height, we added the sentence as follows:

"*Especially, in the tropical and midlatitudes, subvisible cirrus clouds can reach to the upper tropopause (Gierens and Spichtinger, 2000; Immler et al., 2008). Subvisible cirrus generally occurs at the ice supersaturated regions, and can form in situ or as a consequence of deep convection (Krämer et al., 2009; Froyd et al., 2010).*"

In addition, we identified that the occurrence frequency of subvisible cirrus was highest at tropic western Pacific, and found the mean CTHs were significantly larger than other regions (Figure 10). Additional text was added in Section 3.3 Near-global vertical distribution of CVS, as follows:

"*Note the mean CTHs at tropic western Pacific are significantly larger than other regions, reaching up to 12 km. At this region, the occurrence frequency of subvisible cirrus is highest (data not shown). This can be explained that deep convection mostly occurs at tropic areas, favoring the formation of subvisible cirrus (Krämer et al., 2009; Froyd et al., 2010). These results are consistent with previous studies based on satellite observations (Martins et al., 2011; Schoeberl et al., 2022).*"

Reference:

Froyd, K. D., Murphy, D. M., Lawson, P., Baumgardner, D., and Herman, R. L.: Aerosols that form subvisible cirrus at the tropical tropopause, Atmos. Chem. Phys., 10, 209–218, https://doi.org/10.5194/acp-10-209-2010, 2010.

Gierens, K. and Spichtinger, P.: On the size distribution of ice supersaturated regions in the upper troposphere and lowermost stratosphere, Ann. Geophys., 18, 499–504, https://doi.org/10.1007/s00585- 000-0499-7, 2000.

Immler, F., Treffeisen, R., Engelbart, D., Krüger, K., and Schrems, O.: Cirrus, contrails, and ice supersaturated regions in high pressure systems at northern mid latitudes, Atmos. Chem. Phys., 8, 1689–1699, https://doi.org/10.5194/acp-8-1689-2008, 2008.

Krämer, M., Schiller, C., Afchine, A., Bauer, R., Gensch, I., Mangold, A., Schlicht, S., Spelten, N., Sitnikov, N., Borrmann, S., de Reus, M., and Spichtinger, P.: Ice supersaturations and cirrus cloud crystal numbers, Atmos. Chem. Phys., 9, 3505–3522, https://doi.org/10.5194/acp-9-3505-2009, 2009.

Martins, E., Noel, V., and Chepfer, H.: Properties of cirrus and subvisible cirrus from nighttime Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), related to atmospheric dynamics and water vapor, J. Geophys. Res.-Atmos., 116, D02208, https://doi.org/10.1029/2010JD014519, 2011.

Schoeberl, M., Jensen, E., Wang, T., Taha, G., Ueyama, R., Wang, Y., DeLand, M., and Dessler, A.: Cloud and aerosol distributions from SAGE III/ISS observations, J. Geophys. Res.-Atmos., 126, e2021JD035550, https://doi.org/10.1029/2021JD035550, 2022.

28. Section 3.6: I generally agree with the conclusions presented in this section.

Response: Thanks.

29. The conclusions section is a good summary, though may need to be updated depending on what the authors choose to do in addressing my comments across the previous sections.

Response: Thanks. We added the result related to subvisible cirrus in the conclusions, as follows:

"*The mean CTHs are highest at tropic western Pacific, where subvisible cirrus mostly occurs.*"