Reviewer #2

General Comments ∗ 1

> There is a lot of really interesting material here, but it seems somewhat unfocused and in places a little confusing. The manuscript is way too long for the average reader, I suggest tightening it up quite a bit and or consider writing two papers.

Answer: Thank you very much for your time and effort spending on this manuscript and for your helpful comments and suggestions. We have reorganized the structure of manuscript.

General Comments ∗ 2

> SIC in the stratosphere might suggest moistening (as the authors state), but interest in that process is mostly associated with convection penetrating the tropical tropopause. In this paper, the extra-tropical and tropical SIC are sort of lumped together.
>
> For example, SIC moistening in the stratospheric extra-tropics is unimportant since air is moving downward there and will soon exit the stratosphere. Whereas SIC in the tropics is very important since air is moving upward and SIC could be changing the water vapor budget. I guess my point is to wade through 34 pages of material here, the motivation could be clearer.

Answer: Most SICs are observed in the tropics which is of interest for the stratospheric moistening. Meanwhile, the SICs detected in the extra-tropics are also important to understand the physical processes of their formation mechanisms and water vapor transport in the lowermost stratosphere, for example, the convection at midlatitudes (Zou et al., 2021), isentropic transport from TTL (Spang et al., 2015), and the distribution of water vapor in the UTLS is associated with radiative effects that impact the global surface temperature (Riese et al., 2012).

General Comments ∗ 3

> I think the correlation with gravity waves is really part of the correlation with tropopause temperatures and isn't a separate effect. In Fig. 5 you see that the correlation maps (5a) and (5b) are nearly identical. As noted below, the cold temperatures are due to a number of things and gravity waves will be one of them, I am not sure how you separate them in a correlation sense, but I am pretty sure they overlap.

Answer: Yes, tropopause temperatures, gravity waves and deep convection have strong correlations. In our study we could not separate their contributions to the occurrence of SICs. In the revised manuscript, the correlations between SIC frequencies and them are presented separately, but we added a discussion of their inherent correlations in Sect. 3.7.

'The occurrence of SICs has a general negative correlation with tropopause temperature, while SICs have positive correlations with UTLS clouds, gravity waves and stratospheric aerosols. The highest negative and positive correlations are mostly observed over the tropical continents and the western Pacific with correlation coefficients of < -0.8 between SICs and LRT1-T and > 0.8 between SICs and UTLS clouds, gravity waves, and stratospheric aerosols. High positive correlations are also found over the Asian Monsoon and the North American Monsoon regions between SICs and UTLS clouds, gravity waves, and aerosol. While the LRT1-T shows a general negative correlation, there are strong positive correlations over central America and the Caribbean Sea, Philippines and South Chinese Sea, and the Tibetan Plateau to the Caspian Sea. The highest correlation coefficients are as large as 0.8-1.0 in the North American Monsoon region, even for LRT1-T. In the Asian Monsoon region, negative correlations are detected over the Tibetan plateau, but positive correlations are seen over southern Asia and India between SICs and LRT1-T. High correlation coefficients imply the important role of tropopause temperature, UTLS clouds, gravity waves and stratospheric aerosols for the occurrence of SICs. However, overlapping high correlation coefficients indicate also strong connections between the tropopause temperature, UTLS clouds, gravity waves, and stratospheric aerosols themselves.

To further investigate the source of SICs, the highest and second-highest correlation coefficients between SICs and all processes for each grid box are shown in Fig. 11. Over the tropical continents, the highest correlation coefficients of SICs relate to tropopause temperature. The highest correlation coefficients are found between UTLS clouds and SICs in the monsoon domains in the latitude range between 15° and 30°, e.g., the North American Monsoon, the Asian Monsoon, the South African Monsoon regions and the La Plata basin. In the central United States, tropopause temperature and UTLS clouds have the highest correlations with SICs. Over Patagonia and the Drake Passage, tropopause temperature and gravtiy waves have the highest correlation with the occurrence of SICs. In the latitude range between 45° and 60°, the strongest correlations are found between SICs and tropopause temperature and gravity waves. However, the second-highest correlation coefficients of SICs are related to stratospheric aerosols, UTLS clouds, and gravity waves over the tropical continents, the North American Monsoon and the Asian Monsoon regions. The rather similar correlation coefficients of SICs with all processes indicate high correlations between all processes themselves.

For all processes, increased tropopause-penetrating convection may result in a cooler tropopause across the tropics (Gettelman et al., 2002). Gravity waves and wave breaking will locally cause a colder temperature in the atmosphere and air cooling (Dinh et al., 2016). High correlations were found between deep convection and gravity waves (Hoffmann et al., 2013), and vertical motion of air will transport aerosols into the stratosphere (Bourassa et al., 2012). The inherent correlations between all processes may help to explain the positive correlations between SICs and LRT1-T in the North American Monsoon and the Asian Monsoon regions. Even if the tropopause temperature is warm, UTLS clouds, gravity waves, and stratospheric aerosol could all contribute to the high occurrence frequency of SICs. For example, Fu et al. (2006) discovered that deep convection in the Asian Monsoon injected more ice and water vapor into the stratosphere with warmer tropopause temperatures. However, their strong correlation also makes it challenging to disentangle all processes' effects on the occurrence of SICs. '

General Comments $*$ 4

> The SIC correlation with aerosols is interesting, but aerosols are associated with fires as well as volcanoes. The CALIPSO measurements are a direct measure, I don't see how SO2 adds anything to this analysis. You should also mention more clearly why you are correlating with aerosols. Basically, aerosols provide CN and thus clouds form at lower RH so cloud formation should be approximately correlated with aerosols if the environment is at saturation. Volcanic eruptions and fires contain a lot of water so there might be other things going on. I would argue that this whole analysis might be a separate and interesting paper. BTW, OMPS-LP also produces an excellent aerosol data set that is independent of CALIPSO.

Answer: Indeed, stratospheric aerosols from CALIPSO include aerosols associated with volcanic eruptions as well as fires. The SO_2 data was not investigated in detail, but rather used as a proxy for strong volcanic eruptions to indicate stratospheric aerosol that originated from volcanic eruptions or not.

The correlation with stratospheric aerosol is shown, because we realized that SIC anomalies (Fig. 8) coincide with enhanced volcanic aerosol. We fully agree that this finding deserves a more detailed investigation. However, although volcanic injections also contain enhanced water vapour and condensation/ice nuclei that were shown to lead to cloud formation in the troposphere, we cannot fully rule out classification artefacts in the CALIPSO data set, especially for ash-rich volcanic plumes. Using other aerosol data sets, such as the suggested OMPS-LP, would be very helpful. Yet, this was not the scope of our study, so we focused on showing the global correlation and discussed the potential implications and uncertainties in the discussion section.

General Comments * 5

One question I was left with is: Do SIC occurrences well above the tropopause differ from those that are near the tropopause. Your statistics in Figure 1 suggest occurrences up to about 1 km above, but are the outliers very different? Those clouds have more of a potential of moistening the stratosphere.

Answer: Based on Figure 1 in the manuscript, we found that most ice clouds are observed around the tropopause. As you pointed out, there are approximately 1 % of ice clouds with tops 1 km above the tropopause. We didn't discuss those ice clouds separately from all SICs. However, for your interest, we present those ice clouds with cloud tops ≥ 1 km above the tropopause here in Fig. 1. Those ice clouds are mainly observed over the tropical continents in all seasons and also over central North America in JJA. They would be highly related to the deep convection (Fig. 5 in the manuscript).

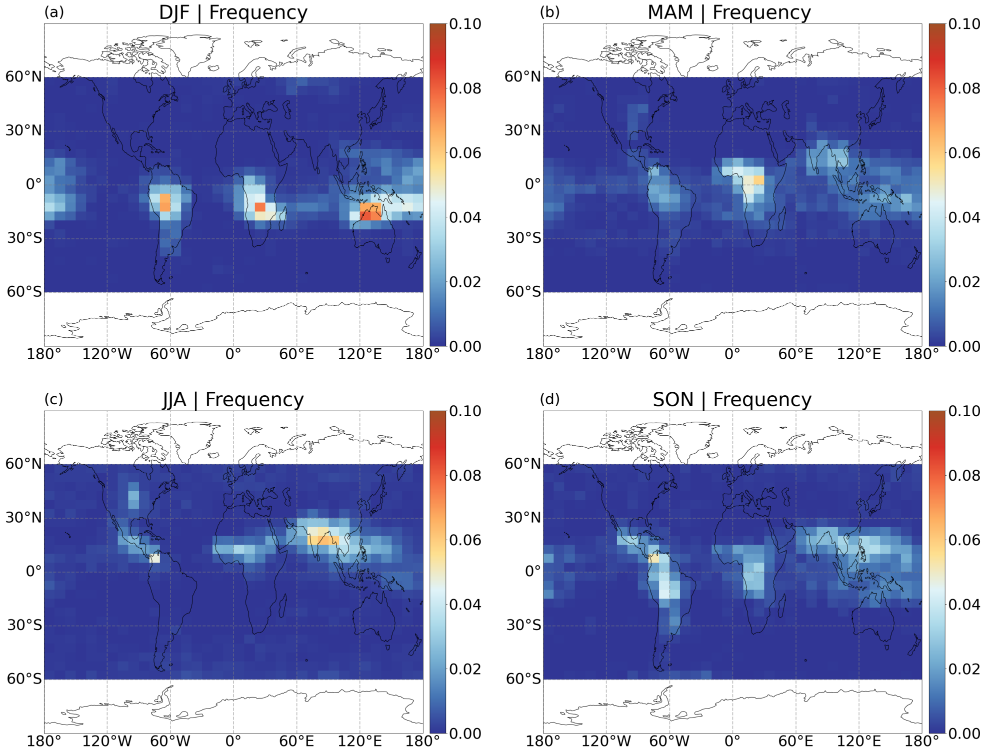

Figure 1: Occurrence frequencies of ice clouds with cloud tops ≥ 1 km above the tropopause.

General Comments * 6

Please focus Abstract on salient points, it is way too long.

Answer: Thank your for your suggestion. We have revised the abstract in the manuscript.

'Ice clouds play an important role in regulating the water vapor and influencing the radiative budget in the atmosphere. This study investigates stratospheric ice clouds (SICs) based on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO). Tropopause temperature, double tropopauses, clouds in the upper troposphere and lower stratosphere (UTLS), gravity waves and stratospheric aerosols, were analyzed to investigate their relationships with the occurrence and variability of SICs in the tropics and at midlatitudes.

We found that SICs with cloud top heights of 0.25 km above the first lapse rate tropopause are mainly detected in the tropics. Monthly time series of SICs from 2007 to 2019 show that high frequencies of SICs follow the Intertropical Convergence Zone (ITCZ) over time in the tropics and that SICs vary inter-annually at different latitudes. Results show that SICs associated with double tropopauses, which are related to poleward isentropic transport, are mostly found at midlatitudes. More than 80 % of the SICs around 30°N/S are associated with double tropopauses.

Correlation coefficient and long-term anomaly analyses of SICs and all the other processes indicate that the occurrence and variability of SICs are mainly associated with the tropopause temperature in the tropics. UTLS clouds have the highest correlations with SICs in the monsoon regions and the central United States. Tropopause temperature and gravity waves are mostly related to SICs at midlatitudes, especially over Patagonia and the Drake Passage. However, besides the highest correlation coefficients, the cold tropopause temperature, the occurrence of double tropopauses, high stratospheric aerosol loading, frequent UTLS clouds and gravity waves all have high correlations with the SICs. The occurrence and variability of SICs demonstrate a strong dependence on various processes, both locally and temporally.

The overlapping and similar correlation coefficients between SICs and all processes indicate strong associations between all processes themselves. Due to their high inherent correlations, it is challenging to disentangle and evaluate their contributions to the occurrence of SICs on a global scale. However, the correlation coefficient analyses between SICs and all processes and high associations between all processes observed in this study help us better understand the sources of SICs on a global scale.'

Specific Comments:

1. Ln 38 net radiative heating? You need to be careful here. High thick cirrus will produce surface heating by blocking IR cooling to space. Do you mean in situ cooling?

We have rephrased this sentence. 'Ice clouds in the UTLS region produce net radiative heating by trapping outgoing longwave radiation (Zhou et al., 2014; Lolli et al., 2018).'

2. Ln 43 Paragraph starting line 43, I presume you are not including Polar Stratospheric Clouds in this discussion. What does 'high altitude' mean? Above the tropopause?

The 'high altitude' indicates clouds observed in the upper troposphere and lower stratosphere. Yes, polar stratospheric clouds are not discussed in our work. We have revised this sentence in the manuscript. 'Global occurrence of ice clouds in the UTLS is about 20 – 40 % over the world (Liou, 1986; Wylie et al., 1994, 2005).'

3. Ln 59 Sentence starting with 'With … ' makes no sense to me.

We have rephrased this sentence. 'It is critical to have a better understanding of the potential formation mechanisms and maintenance of ice clouds in the UTLS. '

4. Ln 67 Awkward English. 'Nucleation of ice crystals occurs in the presence of cold temperatures.'

This paragraph has been revised.

5. Overall comment on ln 34-119. On one hand this is a very thorough review of the literature, but its goal is occasionally illusive. Here is what I got from 80 lines of text: Ice clouds form in cold temperatures Cold temperatures are due to dynamics. Ice clouds are also injected by convection Aerosols impact cloud formation. I suggest that the reader might benefit from a reorganization of this material along these points.

Thank you, we have reorganized the whole section.

6. Ln 148 Spline interpolation can produce a new minimum temperature which is colder than the adjacent model levels, and the actual location of the minimum between the two model levels is unknown. Given the reliance of this study on the exact location of the tropopause, it seems appropriate to have more extended discussion which occurs later in the paper. Perhaps you could move that here. More explicit discussion of the uncertainty in the tropopause height might me appropriate.

Thank you. We have extended the discussion on the tropopause uncertainty in the revised manuscript in Sect. 2.1 and Sect. 4.1. We have used the same tropopause data as Hoffmann and Spang (2022). They found that, after using spline interpolation, the uncertainty of the first lapse rate tropopause height for ERA5 is in ±200 m at different latitudes compared to the US High Vertical Resolution Radiosonde Data (HVRRD) data and the coarser-resolution Global Positioning System (GPS) data. Therefore, we consider the 250 m tropopause threshold used in our study is reasonable.

'Tegtmeier et al. (2020a) found that LRT1 height differences between ERA5 and Global Navigation

Satellite System-Radio Occultation observations are less than 200 m in the tropics. Based on US High Vertical Resolution Radiosonde Data (HVRRD) data and coarser-resolution Global Positioning System (GPS) data, Hoffmann and Spang (2022) also showed that the uncertainty of the LRT1 heights of ERA5 is in the range of ±200 m at different latitudes. Therefore, a height difference of 250 m with respect to the tropopause is used as threshold for ERA5 data to identify stratospheric ice clouds in this study. One should keep in mind that gravity waves and deep convection are generally important factors influencing the height and variability of the tropopause (Sherwood et al., 2003; de la TORRE et al., 2004; Hoffmann and Spang, 2022).'

'As for the possible impacts of gravity waves and deep convection on the tropopause, Hoffmann and Spang (2022) found much more pronounced effects of gravity waves on the variability of tropopause heights and temperatures for ERA5 than ERA-Interim. However, convection-associated tropopause uplifts are not commonly represented, even in ERA5, due to the limited horizontal resolution of the reanalyses data sets. Since we used the same tropopause data set as Hoffmann and Spang (2022), tropopause uncertainties related to unresolved deep convection would exist in our study.'

7. Ln 157 CALIPSO averages their backscatter data over many profiles – this averaging is the effective along track resolution of the data. You should mention this.

We have revised in the manuscript. 'The vertical resolution of CALIPSO observations varies as a function of altitude. It is 60 m in the altitude range from 8.2 to 20.2 km. In the horizontal the profiles are averaged over 1 km along track distance between 8.2 km and 20.2 km of altitude.'

8. Ln 164 I don't see why you are including daytime aerosols. The S/N during the day drops significantly. If ice cloud detection is affected, aerosols will be worse since their backscatter cross section is smaller.

We agree. We excluded the daytime aerosol data from our study.

9. Ln 169 You should mention earlier that this study is not including PSCs.

We have revised the whole manuscript, presenting only data in ±60° to avoid possible mixing of PSCs and SICs in the high latitudes.

10. Ln 180-190 I am surprised that you are using AIRS for deep convection. MODIS has the same channels (and others) and is more frequently cited for identifying cold cloud tops in the 8 and 10.6 µ channels. Furthermore, MODIS or VIIRS has higher spatial resolution.

Thank you, MODIS and VIIRS would be very helpful for deep convection analyses. But for now, we have only the whole time range of AIRS data at hand and the UTLS clouds retrieved from AIRS can well represent clouds from tropical storms and strong convective events at midlatitudes and high latitudes. MODIS or VIIRS data would be a good choice for our future work.

11. Ln 205 Gravity waves at 4µm are detected in the 30-45 km region (see Hoffmann and Alexander (2010), Fig. 3). These waves, propagating vertically, will have much lower amplitude at their tropopause source. For example, assume the wave is detected with a 0.5 K BT temperature (e.g. Hoffmann and Alexander Fig. 1) and using their the center of the weighting function, this wave is at 40km, then the amplitude of the wave at 18 km will be about 0.05K by energy conservation. There is also a spatial correction, as the wave move from the source it will decrease in amplitude. For example, let's say the wave is detected 1000km from the convective system and the convective system has a radius of 100km. Then the source wave will have an amplitude 3 times larger than the detected wave. The author needs to discuss these possible or indicate why they are unimportant corrections.

We agree it is important to better explain the measurement characteristics of the AIRS gravity wave observations and revised Sect. 2.3.2, accordingly. In particular, we added 'However, it is important to note that BT variances should not be confused with atmospheric temperature variances. The AIRS nadir observation geometry significantly reduces the sensitivity of the BT measurements compared to real atmospheric temperature fluctuations for short vertical wavelength waves. For the BT variances, the response to atmospheric temperature variances is near zero below 30 km of vertical wavelength and increases to about 50% at 65 km of vertical wavelength Hoffmann et al. (2014). With these measurement characteristics, AIRS is mostly sensitive to short horizontal and long vertical wavelengths waves, which are expected to propagate from the tropopause to the upper stratosphere within less than 1 – 2 h and horizontal propagation distances less than a few hundred kilometers. The AIRS BT measurements should be seen as a proxy of gravity wave activity.'

12. Ln 213 The difference between 7.1µ and 7.3µ bands as a method of estimating SO2 assumes you can neglect water vapor which will be important where the tropopause is below 8 km. Volcanic SO2 is more easily detected in the UV bands – OMI on Aura is making those measurements coincident with CALIPSO and AIRS and might be a better choice. I am still unsure why we should even use SO2 data since the aerosols come from CALIPSO and SO2 will not be evident in aerosols due to fires.

The aerosols from CALIPSO are used to explore their relationships with SICs. AIRS SO_2 measurements are an established method to measure volcanic plumes at day and night time (Hoffmann et al., 2014). Since we used CALIPSO nighttime data for SIC detection, we chose AIRS SO_2 data, as it provides nighttime information, in contrast to measurements using UV bands. We are interested in explosive volcanic eruptions with injections into the UTLS region, where AIRS SO_2 measurements are very sensitive. SO_2 data from AIRS are subsidiary used to identify volcanic injections that are related to the enhanced stratospheric aerosol load. To make this clear, we added the following sentences: 'In this work, an SI threshold of 10 K is applied to detect strong explosive volcanic eruptions with injections into the UTLS region.'

13. Ln 227 'over the tropical continents.'

Fixed.

14. Ln 228 Awkward wording… 'The weakest signal..'

We have revised it to 'the lowest frequency of '.

15. Ln 250 SIC associated with double tropopause are clearly an 'edge of the tropics' phenomenon – not surprising since that is where double tropopauses occur. I am not sure why these are important. They aren't contributing to dehydration of the stratosphere and double tropopauses are often associated with cloudy systems so I am not sure of their impact on the radiation budget…

We investigated SICs associated with double tropopauses, because they are closely related to the polar-ward isentropic transport and mixing of water vapor in the lowermost stratosphere. Double tropopause are associated with enhanced transport of water vapour from the tropics to the higher latitudes. Observations of thin ice clouds in the low stratosphere over the northern middle and high latitudes in August 1997 were traced back to tropical high-humidity air (Randel et al., 2007; Spang et al., 2015). Therefore, analyses of SICs associated with double tropopauses will help us understanding the air transport and water vapor variability in the UTLS. We added this discussion in the revised manuscript.

'Following the definition of the WMO, a second tropopause is identified if the average lapse rate at any level and at all higher levels within one kilometer exceeds 3° C/km above the first tropopause. The existence of a second tropopause indicates a less stable temperature structure in the UTLS region (Homeyer et al., 2014). Randel et al. (2007) discovered that the double tropopause indicates a region of enhanced transport from the tropics to higher latitudes. Thin ice clouds observed in the low stratosphere over the northern middle and high latitudes in August 1997 originated from tropical high-humidity air (Spang et al., 2015). Therefore, SICs detected in the vicinity of double tropopauses are probably related to quasi-isentropic transport of humid air from the tropics to the extratropics.'

16. Ln 275 Kim et al. emphasized the cooling rate, not just the low temperature was associated with cirrus. Obviously, you need to have a saturated environment for clouds to form, cooling the air creates saturation and ice crystals form. But once they form, they fall out so if the air is just cold and not cooling you don't see as many clouds. I think you should clarify this point.

Thank you. This point has been included in the revised manuscript. 'Low temperatures and cooling processes are more favorable for ice formation, and temperature normally has a negative relationship with cirrus cloud frequency (Eguchi and Shiotani, 2004; Kim et al., 2016).'

17. Ln 290, Ln 304-6 What is the explanation for positive correlations? SIC's show up where temperatures are warmer. Ln 306 appear to be guesses. You might consider that the positive correlations are associated with cooling air not cold air as suggested by Kim (see above).

We have revised the text and extended the discussion. The correlation coefficients between the four processes and the SIC frequencies are analyzed together in Sect. 3.7. The positive correlation coefficients between SICs and LRT1 temperature are found in the North American Monsoon and the Asian Monsoon, with high positive correlation coefficients between UTLS clouds, gravity waves, and stratospheric aerosols and SICs. The high SIC frequencies can be produced by ice and water vapor injection from UTLSs, air cooling induced by gravity waves, and more ice nuclei from stratospheric aerosols when the tropopause is warm.

'While the LRT1-T shows a general negative correlation, there are strong positive correlations over central America and the Caribbean Sea, Philippines and South Chinese Sea, and the Tibetan Plateau to the Caspian Sea.'

'The inherent correlations between all processes may help to explain the positive correlations between SICs and LRT1-T in the North American Monsoon and the Asian Monsoon regions. Even if the tropopause temperature is warm, UTLS clouds, gravity waves, and stratospheric aerosol could all contribute to the high occurrence frequency of SICs. For example, Fu et al. (2006) discovered that deep convection in the Asian Monsoon injected more ice and water vapor into the stratosphere with warmer tropopause temperatures. However, their strong correlation also makes it challenging to disentangle all processes' effects on the occurrence of SICs.'

'However, tropopause temperatures cannot explain some remarkable positive anomalies in SIC frequencies. For example, high SICs in November 2010 to January 2011, December 2011, March 2014, and April-May 2018 over the equator and high SIC anomalies in April-July 2011 at 5°N-20°N. We need to note that the cold temperature as well as the cooling of the atmosphere (Kim et al., 2016) are important for the variation of SICs. And the uplifting motions, gravity waves, the El Niño-Southern Oscillation (ENSO) and quasi-biennial oscillation (QBO) and potentially other effects would all impact the temperature and temperature variations (Abhik et al., 2019; Feng and Lin, 2019; Tegtmeier et al., 2020b) associated with SIC variability.'

18. Ln 335 Convection will push the tropopause upward. So what you are doing here is finding the deep convection using AIRS and then interpolating the ERA5 tropopause height onto the point, and if the cloud observations are above the ERA5 tropopause it is a SIC. How do you know you have correctly located the tropopause? In fact, you don't know if the cloud is above or below the tropopause and thus whether it is truly a SIC. You need a coincident temperature profile (perhaps GPS) to prove this. At least give the reader some idea of the uncertainty in these estimates for the tropopause in these cases. BTW, radar measurements over the US coincident with soundings show that convection drives the tropopause upward, collapses and leaves behind a residual cloud. You should quote some of these references to justify your assertions.

Yes, the uncertainties about the tropopause height related to deep convection are challenging to rule out in our data. We have added this discussion to the revised manuscript in Sect. 2.1 and 4.1, respectively.

'One should keep in mind that gravity waves and deep convection are generally important factors influencing the height and variability of the tropopause (Sherwood et al., 2003; de la TORRE et al., 2004; Hoffmann and Spang, 2022).'

'As for the possible impacts of gravity waves and deep convection on the tropopause, Hoffmann and Spang (2022) found much more pronounced effects of gravity waves on the variability of tropopause heights and temperatures for ERA5 than ERA-Interim. However, convection-associated tropopause uplifts are not commonly represented, even in ERA5, due to the limited horizontal resolution of the reanalyses data sets. Since we used the same tropopause data set as Hoffmann and Spang (2022), tropopause uncertainties related to unresolved deep convection would exist in our study. '

19. Ln 349-356 This discussion doesn't add anything to the paper.

This paragraph has been removed from the manuscript

20. Ln 364 'measurements are not significantly observed in tropics' ???

We have revised this sentence in the manuscript. 'Note that due to the wind filtering and visibility effects, gravity waves are not significantly observed in the tropics in AIRS (Hoffmann et al., 2013).'

21. Ln 358-384 Since SICs at high latitudes are correlated with cold temperature anomalies and cold temperature anomalies are correlated with gravity waves, I am not sure I understand how these terms are independent in Fig 5. In fact, the correlation pattern in Fig. 5 are almost identical. I suggest that

you present a map of correlations between temperature anomalies and gravity waves… This might give us more insight as to the causes. More specifically, cold temperature anomalies can be generated by mesoscale events as well as gravity waves. It is of interest to separate the two which I think might be lumped together in your analysis.

We agree that the cold temperature and gravity waves are strongly correlated. The individual plot of correlation coefficients between SICs and the tropopause temperature, gravity waves, UTLS clouds and stratospheric aerosols can show us the relationships of each process with SIC occurrence. As you pointed out, those individual correlation patterns present high correlations between all processes. However, we can't separate them currently. We have added the discussion of their high correlations in Sect. 3.7 in the revised manuscript.

'The occurrence of SICs has a general negative correlation with tropopause temperature, while SICs have positive correlations with UTLS clouds, gravity waves and stratospheric aerosols. The highest negative and positive correlations are mostly observed over the tropical continents and the western Pacific with correlation coefficients of < -0.8 between SICs and LRT1-T and > 0.8 between SICs and UTLS clouds, gravity waves, and stratospheric aerosols. High positive correlations are also found over the Asian Monsoon and the North American Monsoon regions between SICs and UTLS clouds, gravity waves, and aerosol. While the LRT1-T shows a general negative correlation, there are strong positive correlations over central America and the Caribbean Sea, Philippines and South Chinese Sea, and the Tibetan Plateau to the Caspian Sea. The highest correlation coefficients are as large as 0.8-1.0 in the North American Monsoon region, even for LRT1-T. In the Asian Monsoon region, negative correlations are detected over the Tibetan plateau, but positive correlations are seen over southern Asia and India between SICs and LRT1-T. High correlation coefficients imply the important role of tropopause temperature, UTLS clouds, gravity waves and stratospheric aerosols for the occurrence of SICs. However, overlapping high correlation coefficients indicate also strong connections between the tropopause temperature, UTLS clouds, gravity waves, and stratospheric aerosols themselves.

To further investigate the source of SICs, the highest and second-highest correlation coefficients between SICs and all processes for each grid box are shown in Fig. 11. Over the tropical continents, the highest correlation coefficients of SICs relate to tropopause temperature. The highest correlation coefficients are found between UTLS clouds and SICs in the monsoon domains in the latitude range between 15° and 30°, e.g., the North American Monsoon, the Asian Monsoon, the South African Monsoon regions and the La Plata basin. In the central United States, tropopause temperature and UTLS clouds have the highest correlations with SICs. Over Patagonia and the Drake Passage, tropopause temperature and gravtiy waves have the highest correlation with the occurrence of SICs. In the latitude range between 45° and 60°, the strongest correlations are found between SICs and tropopause temperature and gravity waves. However, the second-highest correlation coefficients of SICs are related to stratospheric aerosols, UTLS clouds, and gravity waves over the tropical continents, the North American Monsoon and the Asian Monsoon regions. The rather similar correlation coefficients of SICs with all processes indicate high correlations between all processes themselves.

For all processes, increased tropopause-penetrating convection may result in a cooler tropopause across the tropics (Gettelman et al., 2002). Gravity waves and wave breaking will locally cause a colder temperature in the atmosphere and air cooling (Dinh et al., 2016). High correlations were found between deep convection and gravity waves (Hoffmann et al., 2013), and vertical motion of air will transport aerosols into the stratosphere (Bourassa et al., 2012). The inherent correlations between all processes may help to explain the positive correlations between SICs and LRT1-T in the North American Monsoon and the Asian Monsoon regions. Even if the tropopause temperature is warm, UTLS clouds, gravity waves, and stratospheric aerosol could all contribute to the high occurrence frequency of SICs. For example, Fu et al. (2006) discovered that deep convection in the Asian Monsoon injected more ice and water vapor into the stratosphere with warmer tropopause temperatures. However, their strong correlation also makes it challenging to disentangle all processes' effects on the occurrence of SICs.'

22. Ln 385 I am not sure why you are even using the AIRS SO2 since CALIPSO measurement of aerosols is more of a direct measure of the influence of aerosols on cloud formation. Furthermore, aerosols are also due to fires (see the anomaly at end of the period shown in Fig. 10 which is the Australian fires.) – see major comments.

Please see answers to general comment no. 4 and specific comment no. 12. CALIPSO aerosol contains aerosol of various origins. To get an idea, which aerosol coincides with SICs we used AIRS SO_2 data to mark volcanic eruptions. This shows that mainly volcanic aerosol coincides with SIC anomalies, but also wild fires, such as in 2017 over North America. However, the Australian bush fires 2009 and 2019/2020 do not coincide with SIC anomalies.

23. Ln 427 Spearman

    Fixed.

24. Ln 460 Table not Tab.

    Fixed.

25. Ln 467 where did 'Atmospheric Turbulence' estimation come from?

    We have revised this sentence in the manuscript.

26. Ln 481, 485 Fig. 6a

    Revised.

27. Ln 475 to 485. This is a very interesting discussion but still does not incorporate the point that deep convection can push up the tropopause so that SIC observations that are apparently above the tropopause are actually in the troposphere. Unless a GNSS RO measurement is made exactly at the right spot, the ERA5 reanalysis will place the tropopause at the wrong altitude.

Please see answers to specific comment no. 18. The discussion of tropopause uncertainties related to deep convection has been added to the revised manuscript in Sect. 2.1 and 4.1. The tropopause height uncertainties aren't yet ruled out in our tropopause data.

'One should keep in mind that gravity waves and deep convection are generally important factors influencing the height and variability of the tropopause (Sherwood et al., 2003; de la TORRE et al., 2004; Hoffmann and Spang, 2022).'

'As for the possible impacts of gravity waves and deep convection on the tropopause, Hoffmann and Spang (2022) found much more pronounced effects of gravity waves on the variability of tropopause heights and temperatures for ERA5 than ERA-Interim. However, convection-associated tropopause uplifts are not commonly represented, even in ERA5, due to the limited horizontal resolution of the reanalyses data sets. Since we used the same tropopause data set as Hoffmann and Spang (2022), tropopause uncertainties related to unresolved deep convection would exist in our study. '

28. Ln 494 It seems to me that the event frequency will over emphasize the SIC occurrence above convection. If you're trying to connect these observations with stratospheric hydration (which is why I am interested in this) then occurrence frequency is the appropriate measure. If you are interested in the morphology of these events, then event frequency is appropriate. It might help to discuss some of these issues at the beginning of this section to motivate the reader.

The event frequency is defined as the ratio of number of days in which UTLS clouds or SICs (≥1 detection) occurs to the total number of days in a given time period over a given region, which is used to eliminate the morphological effects of UTLS clouds in this study. The clarifications have been extended in the revised manuscript.

'Next to the occurrence frequencies, the event frequency is defined in this work as the ratio of number of days in which UTLS clouds or SICs (≥1 detection) occur to the total number of days in a given time period over a given region. The event frequency helps overcome some of the limitations related to cloud geometries for UTLS clouds and SICs.'

29. Ln 511 OMPS-LP makes aerosol limb measurements and is active for most of the period you studied.

Thank you. The suggested OMPS-LP would be very helpful for aerosol studies. We will consider this high vertical resolution data in our future work.

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