Dear editor and reviewer,

Thank you very much for handling and reviewing our manuscript and providing helpful comments. We considered all of the comments and revised the manuscript carefully. Please find our point-by-point replies below.

Reply to the editor

Specific Comments:

1. You should make clear from the outset that UTLS clouds as used in your work relate to the outcome of a specific data set. This would help to clarify the difference between UTLS clouds and SIC. IT should also be emphasized even stronger (already in the Abstract) that your definition of SIC excludes PSCs and what differentiates the two types of stratospheric clouds.

Thank you. We have added the explanation of UTLS clouds and the statement of PSC exclusion to the abstract.

'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) in the latitude range between $\pm 60^{\circ}$ based on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO). As polar stratospheric clouds include other particles, they are not discussed in this work. 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 250 m above the first lapse rate tropopause are mainly detected in the tropics. Monthly time series of SICs from 2007 to 2019 show that high occurrence 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 coefficients of SICs and all the other above-mentioned processes confirm that the occurrence and variability of SICs are mainly associated with the tropopause temperature in the tropics and at midlatitudes. UTLS clouds which are retrieved from the Atmospheric Infrared Sounder (AIRS) and are used as a proxy for deep convection in the tropics and high altitude ice cloud sources at midlatitudes, have the highest correlations with SICs in the monsoon regions and the central United States. Gravity waves are mostly related to SICs at midlatitudes, especially over Patagonia and the Drake Passage. However, the second highest correlation coefficients show that the cold tropopause temperature, the occurrence of double tropopauses, high stratospheric aerosol loading, frequent UTLS clouds and gravity waves are highly correlated with the SICs locally. The long-term anomaly analyses show that inter-annual anomalies of SICs are more correlated with the tropopause temperature and stratospheric aerosols instead of the UTLS clouds and gravity waves.

The overlapping and similar correlation coefficients between SICs and all processes mentioned above indicate strong associations between those 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 above-mentioned processes (tropopause temperature, double tropopauses, clouds in the upper troposphere and lower stratosphere (UTLS), gravity waves and stratospheric aerosols) in this study help us better understand the sources of SICs on a global scale.'

2. line 54: This statement is somewhat confusing. You mean that convective clouds inject ice directly rather than form ice clouds?

We have revised the sentence. 'Convective systems form ice clouds directly from anvil outflow, as well as indirectly from updrafts and wave-induced cooling'

3. lines 80-82: no need to introduce subsections in the introduction - line 87 and later: laps rates should be given in K/km

Revised. 'Section 3 presents the global SICs and relationship analyses between SICs and double tropopause, tropopause temperature, UTLS clouds, gravity waves, and stratospheric aerosols. Section 4 discusses the data uncertainties and relationship uncertainties between SICs and above-mentioned processes. Conclusions are presented in Section 5.'

4. line 89: criterion (singular)

Fixed.

5. line 118: Please be specific what's meant with high feature type quality.

The explanation is added to the manuscript. 'Samples marked with high feature type quality (the absolute value of the CAD score $\geq$70) are used to ensure high reliability of data.'

6. line 125 and later: latitude range below 60 degree

Fixed.

7. Caption of Figure 1: please note in the caption what different line colours refer to and state the meaning of the hatched area

Thanks. We revised the caption. 'Occurrence frequencies of SICs on a $5^\circ \times 10^\circ$ (latitude $\times$ longitude) grid (a-d) and occurrence frequencies of ice cloud top heights (CTHs) in the altitude range from -4 to 4 km with respect to the first thermal tropopause (e-h) in DJF, MAM, JJA and SON from CALIPSO measurements. In e-h, the data are shown as zonal averages, globally (gray bars), for the tropics (20° S - 20° N, orange lines) and midlatitudes (40° -60° green lines for NH and purple lines for SH). The hatched areas are tropopause uncertainties of $\pm$250 m.'

8. line 227: should be 250 m or 0.25 km?

Revised, and the manuscript is unified using 250 m.

9. Figure 4 (and later): it might be nice to point out that the lines represent the data shown in Figure 1a-d?

We have added this explanation to all corresponding figures.

'Figure 4. Seasonal mean first tropopause temperature from ERA5 (color boxes) and occurrence frequencies of SICs from CALIPSO shown in Figure 1a-d (contour lines with an interval of 0.12).

Figure 5. Seasonal event frequency of UTLS clouds derived from AIRS during 2007-2019. Occurrence frequencies of SICs (data in Figure 1a-d) are shown in black contours with the interval of 0.12.

Figure 7. Mean brightness temperature variance at 4.3 μm from AIRS measurements, which correlates with the amplitude of gravity waves. Black contours are occurrence frequencies of SICs shown in Figure 1a-d.'

10. Figure 7: Why are contours no longer in black as in the other plots?

We have updated all figures with black contours for SIC occurrence frequencies.

11. lines 301-310 and Figure 8 could be omitted. Alternatively, a correlation plot might be the better way to go here.

We have removed Figure 8 from the manuscript. The correlations between SICs and SAs are presented together with other processes in Section 3.7 for an overall analysis of all processes.

12. lines 323-326: should be moved to the caption of Figure 10

Revised.

Reply to reviewer #1

General Comments

> I acknowledge the significant efforts made by the authors to improve their paper. Figure 11 is a nice addition. The article has been almost entirely rewritten – the track changes shows red or blue everywhere except in the bibliography. I am not currently able to re-review the entire article and check all the additions and changes, but based on the reply to reviewers and the parts of the revision I've read I would say that weak points remain in the manuscript and in some parts the writing appears rushed. The abstract especially needs work. I have comments below that I think still need to be addressed.
>
> Note that I have identified problematic writing and thinking in the parts of the revision that were relevant to the original comments I raised, but there is no reason to believe that the rest of the revision is problem-free.

Answer: We appreciate your comments and suggestions for improving the manuscript, and we have revised the manuscript based on all the specific comments. Please see our point-by-point replies below.

Specific Comments:

1. abstract, line 12: "correlation coefficient ... indicate" – perhaps "confirm" would be better here. The fact that high clouds are driven by the tropopause temperature is not a new result.

Revised. 'Correlation coefficients of SICs and all the other above-mentioned processes confirm that the occurrence and variability of SICs are mainly associated with the tropopause temperature in the tropics and at midlatitudes.'

2. abstract, lines 12-15: You first say that the occurrence and variability of SIC are mainly associated with tropopause temperature in the Tropics. Then you say the Tropopause temperatures are *mostly* related to SIC in the midlatitudes – this implies that tropopause temperatures are *less* related to SIC elsewhere, for instance in the tropics (and you just said that they are). Please clarify by just stating upfront that SIC are primarily driven by tropopause temperature in both Tropics and midlatitudes.

We have revised those sentences.

'Correlation coefficients of SICs and all the other above-mentioned processes confirm that the occurrence and variability of SICs are mainly associated with the tropopause temperature in the tropics and at midlatitudes.'

'Gravity waves are mostly related to SICs at midlatitudes, especially over Patagonia and the Drake Passage.'

3. abstract, lines 14-15 : "besides the highest correlation coefficients" I don't understand what this means.

We have rephrased the sentence. 'However, the second highest correlation coefficients show that the cold tropopause temperature, the occurrence of double tropopauses, high stratospheric aerosol loading, frequent UTLS clouds and gravity waves are highly correlated with the SICs locally. The long-term anomaly analyses show that inter-annual anomalies of SICs are more correlated with the tropopause temperature and stratospheric aerosols instead of the UTLS clouds and gravity waves.'

4. abstract, lines 17-18: "The occurrence and variability of SICs demonstrate a strong dependence on various processes": Everything has a strong dependence on various processes. This sentence says nothing of value and can be omitted.

We have removed this sentence from manuscript.

5. abstract, line 19: "... and all processes" All processes means all processes, i.e. even those you have not considered in the paper. Please rephrase.

We have rephrased the sentence. 'The overlapping and similar correlation coefficients between SICs and all processes mentioned above indicate strong associations between those processes themselves.'

6. lines 100-106: This addition to the paper is very interesting and the justification very convincing. Thanks.

Thank you for this encouraging comment.

7. lines 123-125 in the revision, and answer to general comment 2: If you limit your analyses to the latitude range of ±60°, there is not point in excluding clouds with CTHs above 12km at latitudes ¿60°. Please simplify your description.

We have revised this sentence to 'In this study, analyses are limited to the tropics and midlatitudes (±60°) to avoid interferences with the polar stratospheric clouds (PSCs).'

8. line 165: it is still unclear to me why stating that AIRS observations have the highest sensitivity at 30-40km requires referencing 3 Hoffmann papers. One would be enough.

We have retained only one reference in the revised manuscript.

9. line 214: "At midlatitudes, the frequencies of SICs at midlatitudes..." line 214: I don't understand "at least twice as low as in the Tropics".

We have revised this sentence. 'At midlatitudes, SICs are observed at least two times less frequently than in the tropics.'

10. line 201-204: I don't understand where the vertical distributions of ice clouds presented in figures 1e-h come from. Are those results from CALIPSO? From AIRS? Are the plots showing the distribution of ice cloud top heights (as the vertical label suggests) or are those profiles of cloud fraction (as CALIPSO retrievals provide)? I am surprised that the midlatitude frequencies are mostly as large as the Tropics frequencies (while the maps show that SIC are much more frequent in the Tropics), are the distribution normalized? If they are you should say it. You need to better describe what is being shown here.

All the data presented in Figure 1 is from CALIPSO. Figure 1e-f shows the vertical distribution of ice cloud top heights. We have updated the figures and text in the manuscript. The similar occurrence frequencies of ice clouds in the tropics and midlatitudes in JJA can be affected by the location of ice cloud hotspots as the averaged values in the latitude range between 20° S - 20° N are presented in Figure 1g.

'Vertically, ice cloud top heights (CTHs) observed in CALIPSO are mostly found in the tropopause region (± 500 m around the tropopause). Seasonally and regionally averaged occurrence frequencies of ice cloud top heights as a function of altitude are shown in Fig. 1 e-h for the tropics (20° S - 20° N) and midlatitudes (40° -60°N/S). Most ice cloud top heights are observed around the tropopause in the tropics and at midlatitudes. In the tropics, about 1 % of ice clouds have cloud tops 1 km above the tropopause in DJF, MAM, and SON. But very few ice clouds are found at midlatitudes with cloud tops 1 km above the tropopause. In JJA, relative low occurrence frequencies of ice clouds above the tropopause in the tropics can be affected by the location of ice cloud hotspots as we presented the averaged values in the latitude range between 20° S - 20° N.'

11. I'm still not sold on the value of some plots. Figure 2 still shows the evolution of SICs frequencies over 12 years but the discussion (lines 205-213) never mentions interannual variations, only the annual evolution, so what's the point? The discussion of Figure 12 (lines 365-389) is done through eyeball analysis which I find unreliable and unconvincing. This discussion would also be helped by referencing the figures when they are discussed (eg Fig 12a vs Fig 12c, etc). Figure 12d looks particularly useless, and is actually quite puzzling: the text references "high anomalies of UTLS clouds" that I have trouble seeing in the figure. Figure 12d suggests that UTLS clouds almost never happen, and that SIC necessarily originate from other sources. Please clarify.

We discussed the annual evolution of SIC occurrence frequencies in Figure 2 and the interannual variability of SIC anomalies in Figure 11 (Figure 12 in the previous manuscript). The 13 years of data shown in Figure 2 would present and confirm the seasonal features of SIC occurrence frequencies. We have revised the text and added sentences for this explanation. Figure 11 has been updated in the manuscript. We have deleted the UTLS cloud and gravity wave subplots because they do not correlate significantly with the SIC anomalies. The discussion in Figure 11 has been revised accordingly.

'To investigate spatial and temporal variations of SICs, monthly 5° latitude band averaged occurrence

frequencies of SICs from 2007 to 2019 are shown in Fig. 2. Seasonal cycles of SICs are observed in the tropics and at midlatitudes. SICs in the tropics follow the Intertropical Convergence Zone (ITCZ) over time, i.e., high SIC occurrence frequencies in the latitude range of 20° S-20° N move from south to north from boreal winter to summer and north to south from boreal summer to winter. The correlation with the ITCZ suggests that there is a strong correlation with deep convection. Most SICs are observed between 15° S-5° N, which show higher SIC occurrence frequencies (> 0.24) and longer occurrence times (November to March of the following year). The SIC occurrence frequencies are stronger in the SH tropics, whereas SICs extend to higher latitudes in the Northern Hemisphere. Some SICs are identified at 25° N-30° N from June to August, which are absent in the Southern Hemisphere, which would relate to the uplift of the Tibetan Plateau and the Asian Monsoon region. Fig. 2 presents pronounced high SIC occurrence frequencies from November 2010 to January 2011 and relatively low values in 2015–2016 in the tropics. For more detailed inter-annual variability of SIC occurrence frequencies, please see Fig. 11a.'

'To explain the inter-annual variation of SICs, anomalies of SIC frequencies, LRT1 temperature ans SAs at different latitude bands (5° for each band) from 2007 to 2019 are presented in Fig. 11. The anomalieswere computed as the difference between the monthly zonal mean values and the inter-annual mean of the monthly zonal mean values, which excludes seasonal cycles of parameters. The regionally averaged monthly anomalies of SIC occurrence frequencies and all processes with seasonal cycles over the tropics (20° S-20° N), northern midlatitudes (40° N-60° N) and southern midlatitude (40° S-60° S) can be found in Appendix. D.

For global-scale anomalies excluding the effect of seasonal cycles, significant anomalies in SIC occurrence frequency can be observed in the tropics. Anomalies of SIC frequencies at $\pm 20°$ are generally demonstrating contrary features to the LRT1 temperature. Blue boxes in Fig. 11a and b present the negative correlations between SIC anomalies and LRT1 temperature anomalies, for instance, in February 2007 to July 2007, January-October in 2008, October 2012 to June 2013, June 2015 to January 2016, June 2016 to August 2017 and October 2018 to February 2019. During those periods, tropopause temperature variations are important for the anomalous variability of SICs in the tropics. However, tropopause temperatures cannot explain some remarkable positive anomalies in SIC occurrence 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 (Fig. 11a).

Moreover, enhanced stratospheric aerosols due to volcanic eruptions coincide with the high SIC anomalies that are marked in red boxes in Fig. 11a and c, for example, in November 2010 to January 2011 (Merapi volcano), April-July 2011 (Nabro volcano), March 2014 (Mt. Kelud volcano), April-May 2018 (Ambae volcano). In the extra-tropics, the most pronounced positive anomalies in SIC occurrence frequency correlate with the ash rich volcanic eruptions of Kasatochi (August 2008, 52° N), Puyehue-Cordón Caulle (June 2011, 41° S), Calbuco in April-May 2015 (41° S), and Raikoke (June 2019, 48° N) (Fig. 11a and c) (compare with AIRS ash and SO2 index Hoffmann, 2021b). There are no substantial inter-annual correlations between SICs and UTLS clouds and gravity waves. The tempo-spatial analyses of LRT1 temperature and stratospheric aerosols provide explicit awareness of processes on the occurrence and variability of SIC anomalies at different latitude bands and time ranges.'

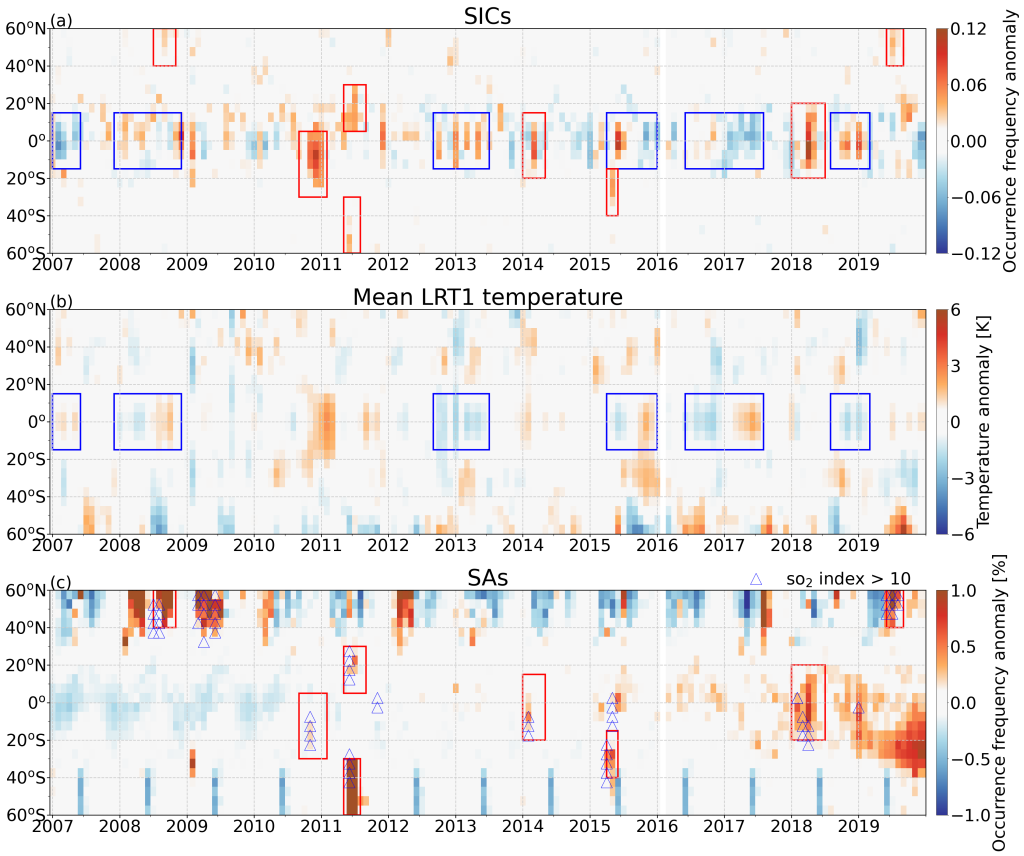

Figure 11: Monthly anomalies of SIC occurrence frequency, LRT1 temperature, stratospheric aerosol occurrence frequency from 2007 to 2019. Blue triangles indicate high SIC occurrence frequency related to strong volcanic events, identified by an SI > 10 K derived from AIRS observations. SIC anomalies that are negatively correlated with LRT1 temperatures are marked with blue boxes (shown in a and b), and those positively correlated with SAs are marked with red boxes (a and c).

12. Figure 1: the color bars need labels and units. The title of the figures say ”Frequency” while the legend says ”Occurrence frequencies”. Is this the same thing? Figures 1e-1h: the x-label requires units.
13. Figure 2 title: ”Mean frquency”. Legend: what is an ”occurrence frequency”? Is it the same as the ”Frequency” that appears in the title? The color bar needs a label and units. Are the data shown percents or something else? Legend: ”latitudes band”
14. The legend of Figure 2 says ”Monthly mean occurrence frequencies” and the legend of Figure 1 only says ”Occurrence frequencies”. Does this mean that the data shown in figure 1 is not averaged somehow? Please use consistent descriptions
15. Figure 3: color bars need labels and units
16. Figure 7: please move ”Mean BT variance [K2]” to the color bar labels from the figure titles.
17. Figure 9: please remove ”Frequency of SAs” from all titles and include it in the colorbar legend

Answer to Points 12-17. Thanks. We have updated all figures. The expression ’occurrence frequency’ has been unified throughout the manuscript.

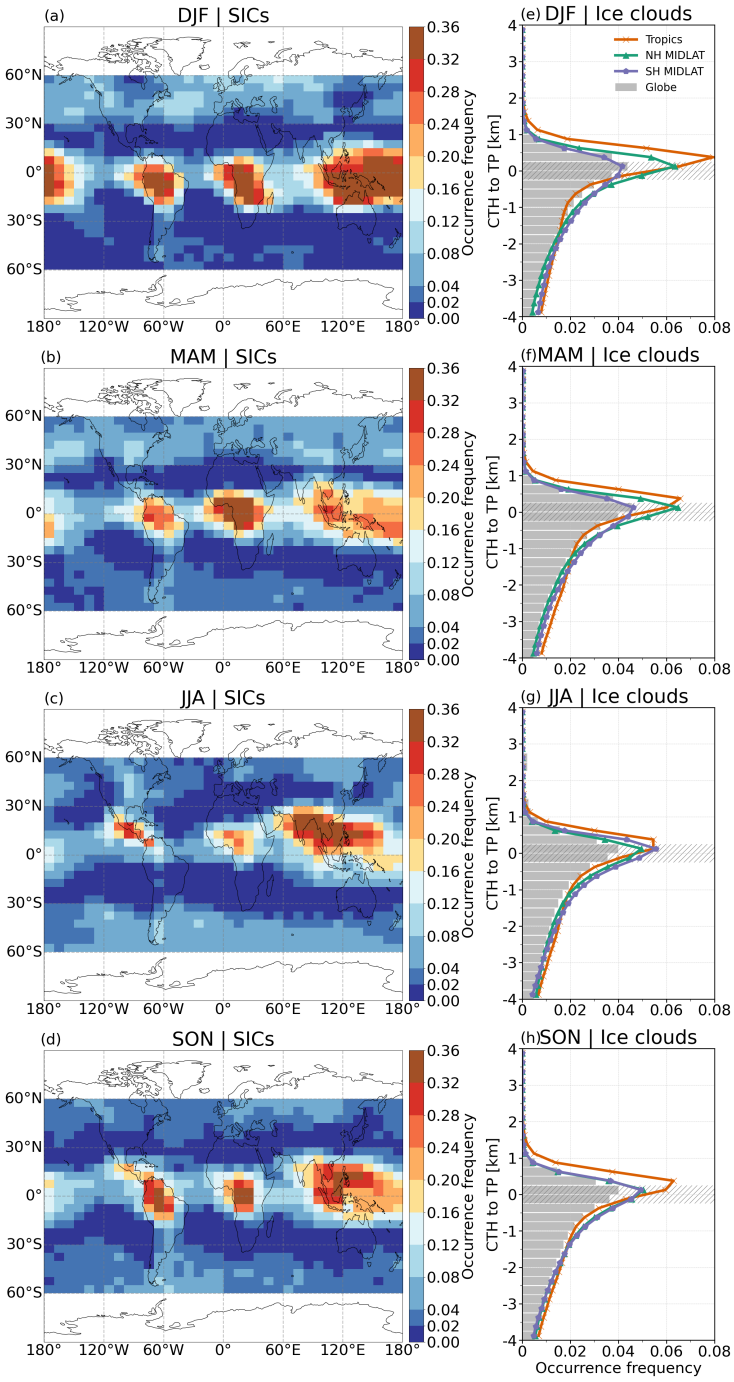

Figure 1: Occurrence frequencies of SICs on a $5° \times 10°$ (latitude $\times$ longitude) grid (a-d) and occurrence frequencies of ice cloud top heights (CTHs) in the altitude range from -4 to 4 km with respect to the first thermal tropopause (e-h) in DJF, MAM, JJA and SON from CALIPSO measurements. In e-h, the data are shown as zonal averages, globally (gray bars), for the tropics ($20° \text{ S} - 20° \text{ N}$ orange lines) and midlatitudes ($40° - 60°$, green lines for NH and purple lines for SH). The hatched areas are tropopause uncertainties of ± 250 m.

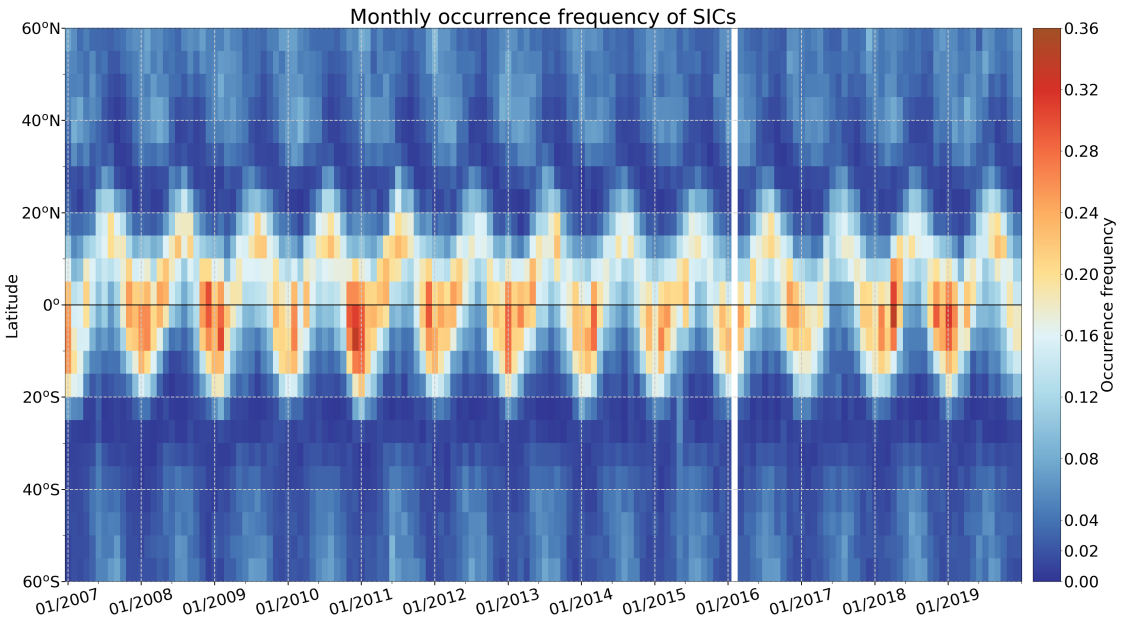

Figure 2: Monthly occurrence frequencies of SICs in latitude band of 5° from 2007 to 2019.

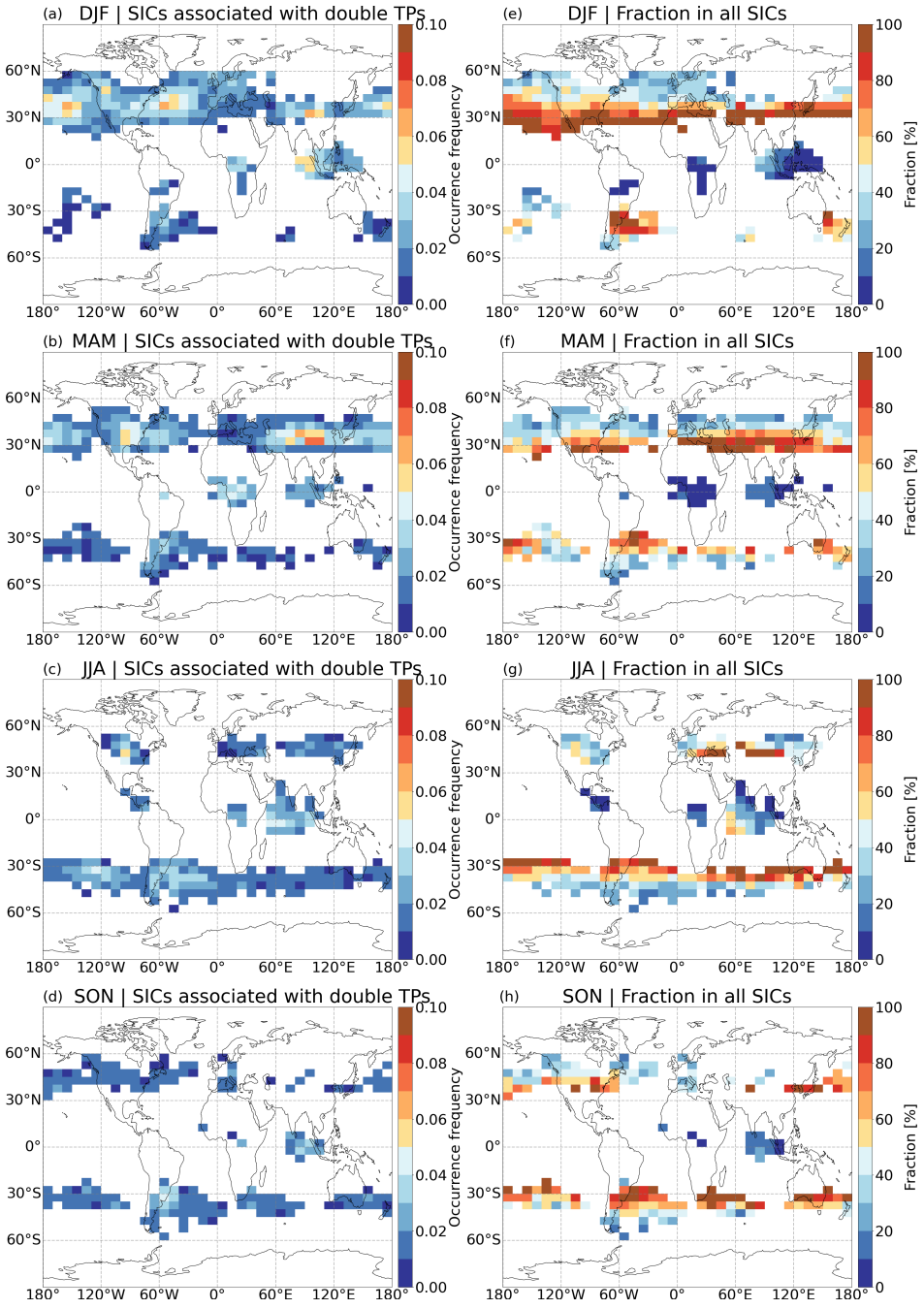

Figure 3: Occurrence frequencies of SICs associated with double tropopauses with respect to all profiles (a-d) and the fraction of SICs associated with double tropopauses to total SICs (e-h).

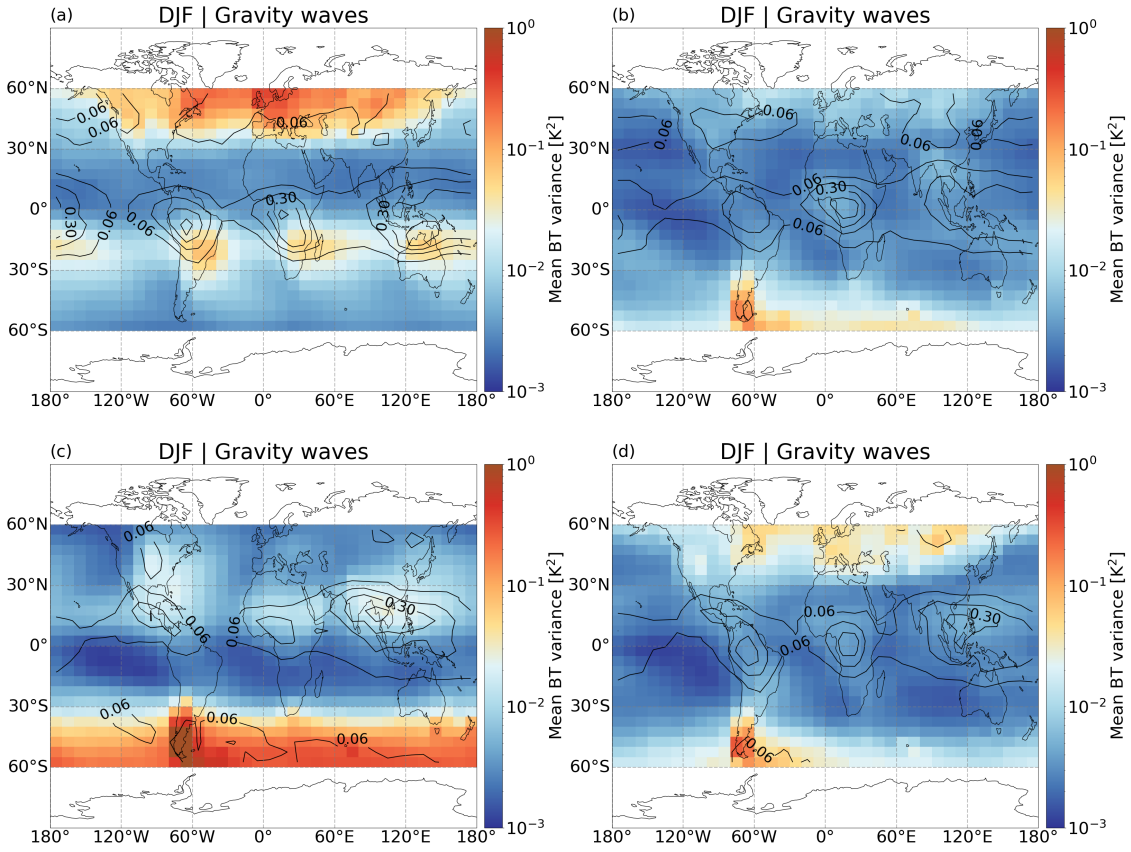

Figure 7: Mean brightness temperature variance at 4.3 μm from AIRS measurements, which correlates with the amplitude of gravity waves. Black contours are occurrence frequencies of SICs shown in Figure 1a-d.

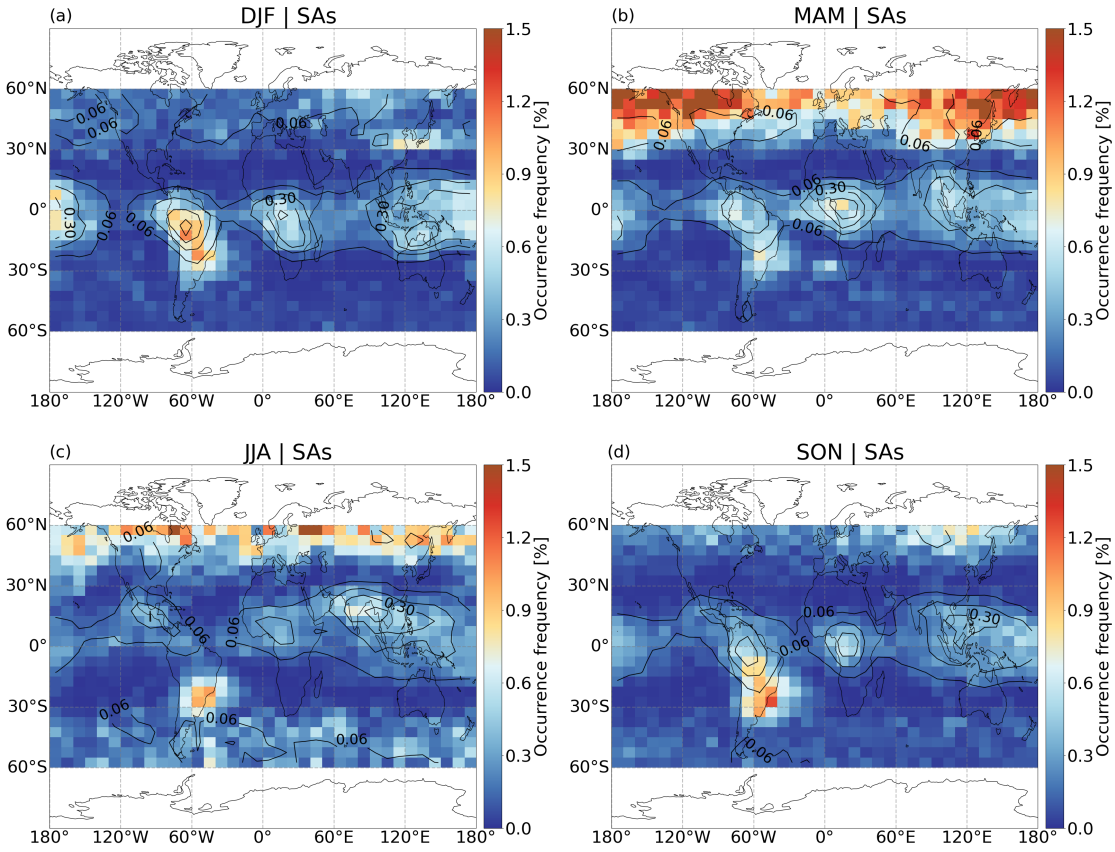

Figure 8: Seasonal occurrence frequency of stratospheric aerosols from CALIPSO during 2007-2019. Black contours are occurrence frequencies of SICs shown in Figure 1a-d.