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Interactive comment on "Cloud-scale ice supersaturated regions spatially correlate with high water vapor heterogeneities" *by* M. Diao et al.

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Response to Reviewers Format: reviewers' comments are quoted between asterisks.

Line number in the response refers to the revised manuscript with highlighted changes.

Quotation stands for revised/added text in the revised manuscript.

Overall comment: We thank the two reviewers for their helpful comments, suggestions and points of clarification. Below are their individual comments, our detailed responses to them, and the corresponding changes to the manuscript where appropriate.

Response to Reviewer #1

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*Summary: This is a study using aircraft data from the START08 and HIPPO missions to examine the spatial scale of ice supersaturated regions (ISSRs) in the upper troposphere. The general conclusion is that, for the regions sampled in this study, spatial variability in water vapor drives more of the variability in ISSRs than spatial variations in temperature.

My main concert regarding this work is whether the authors have considered how the main conclusion may take into account to the larger scale environment the ISSR is embedded within. Reasons for ISSRs have previously been noted to be due to cooling temperatures or, if related to H2O variations, then due to convection or mixing. The statistics in this study indicate that H2O variations are dominant. Why are those H2O variations there? Are these predominantly convective regions? This could be examined by looking at geostationary cloud images.

It would also be useful to try to calculate the history of the parcels considered. If a small sized ISSR is adjacent to a small sized non-saturated region, do the back trajectories diverge? I realize that this is then taking a Lagrangian view of the issue, but since processes occur in a Lagrangian manner, that view cannot be ignored. Your final section implies that this isn't possible on the scales you're looking at. If that is the case, can you at least look to see if the regions with ISS small-scale variability show other evidence for gravity waves or turbulence?*

We appreciate the reviewer for pointing out the importance of large scale environments for the ISSR formation. We note that our observations of the dominance of H2O spatial variability over relative humidity (RH) horizontal spatial variability is a ubiquitous feature from the surface to the tropical upper troposphere (UT) or extratropical lower stratosphere (LS), over both ocean and land, at five different times of the year, and in both hemispheres (shown in new Table 3). This means that the feature happens even at regions with different large scale dynamical backgrounds, such as tropics and polar regions. Two case studies of Spichtinger et al. (2005 a and b) have previously reported that certain large scale dynamics could contribute to the formation of ISSRs in the ex-

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tratropical regions, such as warm conveyor belt and gravity waves. Yet it requires a lot more effort to assess the role of individual types of dynamics in generating this global feature of the strong contribution of H2O variability to RH variability. The analyses deserve a new set of work to case study each type of dynamical background during the ISSR observations. In addition, for the suggestion on back trajectory, it would requires the knowledge of 3-D wind field on ~200 m high resolution on the global scale in order to resolve the origins of these microscale ISSRs, and the current models still have large uncertainties to generate a global wind field at this high resolution. For the suggestion on the contribution of gravity waves, because the HIPPO and START08 campaigns do not target on gravity waves, there were very limited observations on gravity waves with a clear structure. We mentioned this in the first version of manuscript that the gravity wave with "a clearly observable wave structure. . .were not typically seen during the START08 and HIPPO flight campaigns" (22256 Line 16-19). For the suggestion on the contribution of turbulence, we add comments on the necessity of future study to quantify its role in generating H2O spatial variabilities. We feel that if we only focus on one or two dynamical process in generating H2O variability in this work, it would be biased and misleading as if those processes are the dominant cause of the global feature of H2O variability. Thus a more comprehensive work in the future is needed to fully compare each dynamical process in generating H2O variability.

We add comments in the discussion to point out the importance of future work on analyzing the roles of dynamical processes in ISSR formation (Line 629-641): "The formation of the microscale ISSRs are likely attributed to many dynamical processes on various scales. For example, on the microscale, processes such as small scale turbulence, small gravity waves, entrainment mixing and ice crystal sedimentation could generate the microscale spatial variability of H2O, which defines the location and magnitude of microscale ISSRs in the horizontal Eulerian view. On the other hand, mesoscale processes such as uplifting, large scale gravity waves and deep convection could contribute to the overall environment of cooling, which lower T and increase RH in the Lagrangian view. Future work is needed on both scales in order to quantify the contri-

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bution of individual processes to the formation of ISSRs. For example, back trajectory analyses are needed to assess the roles of large scale dynamics in setting the overall cooling environment, while tracer analyses are needed to assess the roles of turbulence and mixing between air masses in contributing to the heterogeneities of H2O field. In particular, specific case studies will be helpful in order to quantify the scales of vertical displacements that can generate the observed H2O variability based on a local H2O profile."

finally, do the conclusions hold at all latitudes? Before using these statistics to test models, I think you need to know whether these results are biased relative to certain conditions. From Figure 1, it appears that most of the flights were over North America. Where do you see most of the ISSRs?

To address whether that our conclusion holds at all latitudes, over ocean and land, as well as at different times of a year, we added new Table 3 and explained in Line 531-537: "In order to examine whether the dominant contribution of H2O variability varies with latitudes, seasons and between over land and ocean, we analyzed the contribution of H2O and T variabilities to the 1 Hz dRHi at different P bins. Table 3 shows that the H2O variability contribution at each pressure bin does not vary significantly when binned by latitude (0–30°N, 30°N–60°N, 60°N–87°N, 0–30°S, 30°S–60°S, 60°S–67°S), nor does it vary between observations over land and ocean, or at different times of a year."

To address whether our overall observation is biased toward certain condition, we added new Table 1 and explained in Line 299-303 that our data has wide coverage in latitudes, T, P and H2O: "The data distribution and sampling range of this work are shown in Table 1. The observations include ∼300 hr and ∼100 hr in the Northern and Southern Hemispheres (NH and SH), as well as ∼310 hr and ∼90 hr in the extratropical (30°S–67°S and 30°N–87°N) and tropical regions (30°S–30°N), respectively. The overall observations of T, P and H2O range from 196–311 K, 133–1039 mb and 1.5–39000 ppmv, respectively."

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To address the question on ISS distribution, we also showed the ISS distribution in new Table 1 and explained in Line 312-317: “For these ISS observations, 87% and 13% of them were in the NH and SH, respectively. In addition, 90% and 10% of these ISS were observed in the extratropical and tropical regions, respectively. We note although there are fewer ISS observations in the SH and tropical regions at T $\leq$ -40 °C, there are still sufficient amount of flight hours in the SH ($\sim$105 hr) and in the tropical regions ($\sim$93 hr) for our analyses of RH variability at all T condition.” We also added clarification on the sampling limit of the NSF GV research aircraft in Line 310-311: “Note that the NSF GV aircraft ceiling ($< \sim$15 km) prevents us from sampling the majority of the Tropical Tropopause Layer.” Thus the conclusion of this work is representative for both NH and SH as well as from 87°N–67°S.

My overall recommendation is that the paper ultimately be published in ACP. However, I’d like to see some consideration of the comments above in revision. Some more editorial type comments are given below.

Specific comments: Page 22252 line 19: For the benefit of those who are not cloud specialists, please explain what a chord length is, or use a different term (perhaps typical horizontal size)

We add clarification to “chord length” in Line 71-72 of the new manuscript: “Recently, Wood and Field (2011) showed that the median chord length (1-D horizontal size) of cirrus clouds is $\sim$1 km based on a combination of in situ aircraft observations, satellite observations and numerical model simulations.”

Page 22256: line 5. . .You should be clear here that you only use CO and O3 from START-08. (Note, the HIPPO master list does not include the NCAR ozone instrument, but rather two NOAA ozone instruments. Because START08 had both a NOAA and NCAR ozone instrument, I assume that is what you’re referring to.)

We add this clarification in Line 172-176 of the new manuscript: “The analyses of O3, CO and ice water content are based on the measurements from the START08

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campaign only. In START08, O3 was measured by the NCAR dual-beam ultraviolet absorption photometer with an accuracy of 5% and precision of 5% (Tilmes et al., 2010)."

Page 22258, line 25: Is the strict horizontal restriction (pressure change less than 1 hPa) necessary? If you don't impose that, how do your results change? (say you use 3 hPa?) I assume the 1 hPa restriction limits the horizontal scales you can consider.

We added the analyses in Line 237-238: "The RHi variability with dP < 10 hPa as well as with no pressure restriction are also analyzed." The results are shown in Line 493-499: "We also analyzed the contribution of H2O variability to the variability of all RHi with two less tight pressure restrictions: 1) dP < 10 hPa and 2) no pressure restriction. The results show that the H2O contribution to dRHi for these two scenarios are 0.93 $\pm$ 0.0004, 0.93 $\pm$ 0.0004 at 1 Hz scale, and 0.84 $\pm$ 0.01, 0.89 $\pm$ 0.03 at 23 km scale, respectively. These results suggest that the pressure restriction does not influence our conclusion of the strong contribution of H2O variability to the RHi variability."

Page 22261 line 4: change notified to noted

Revised.

Discussion of past measurements: page 22261-62: you should note altitude levels for the past measurements. In particular, you should also note that the Kramer 2009 analysis covers temperatures much colder (and probably higher in altitude) than what was sampled during START-08 and HIPPO. For your figure 5, it would be useful to have the temperature scale in K, to be directly comparable to the Kramer 2009 figure.

We added the temperature range for the previous observations that we have compared with, including Krämer et al. (2009), Ovarlez et al. (2002) and Kahn et al. (2009). The clarification is made in Line 336-340: "We note that these past studies were conducted at different temperature and altitude ranges. For example, the current analyses on ISS are at 196–233.15 K; the analyses of Krämer et al. (2009) were at 183–240 K; the

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analyses of Ovarlez et al. (2002) were at ∼210–250 K; the analyses of Kahn et al. (2009) were at T < 243 K and H2O mixing ratio < 15 ppmv, which is below ∼15 km." In addition, we added clarification in Line 344-346: "We note that the observations in Krämer et al. (2009) contain much colder conditions that haven't been sampled in the START08 and HIPPO campaigns due to the flight ceiling restrictions of the GV research aircraft."

Also, we revised Fig. 5 to have temperature scale in K to be more comparable with Krämer et al. (2009).

Page 22263, lines 10-20: I'm just a bit confused as to what figure 6B shows. The blue line, if I've understood correctly, shows a RH as a function of the size of the saturated region. The red and green lines do not appear to be discussed in any detail in the text.

We rewrote three paragraphs to clarify the fit in Fig. 6B for the distributions of 1) ISSR length (red), 2) spacing (green) and 3) RHimax values (blue). In particular, we explained more on the meanings of these fits and the comparison with previous work.

1) To address the ISSR length distribution, we made the following changes:

Line 360-382: "A typical time series of the aircraft observations of RHi (black line), T (red dotted line), H2O (blue) and altitude (green) are shown in Fig. 6A. The ISSR is defined as the region where RHi is consecutively above 100% (thick red line). For each segment of ISSR, we analyze its spatial characteristics in terms of its length and RHimax. In addition, we calculate the spacing between the ISSRs. Here these spatial characteristics are analyzed in a horizontal Eulerian view, since the aircraft's horizontal true air speed is always at least ∼25 times greater than its vertical velocity. The distributions of these characteristics of all 1542 ISSRs are shown in Fig. 6B. The number of events of ISSR length and spacing are shown as red solid dots and green upside down triangles in Fig. 6B, respectively. And the relationship between ISSR length and RHimax value is shown as the blue void triangles. Based on the number of events of ISSR length, the mean and median of ISSR length are 3.5 km

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and 0.7 km, respectively. These values are two orders of magnitudes smaller than the previously reported mean (150 km) and median (50 km) ISSR lengths at ∼15 km resolution (Gierens and Spichtinger, 2000). Because the previous work of Wood and Field (2011) used a power law distribution to fit the distribution of 1-D cirrus cloud chord length, here we also apply a power law fit to the distribution of ISSR lengths (red dotted line in Fig. 6B), that is, log10(Number of events of ISSR) = a + b × log10(ISSR length). The intercept and slope of the fit are 4.7 ± 0.4 and -0.77 ± 0.11, respectively. The ± one sigma represents one standard deviation for all linear fit in this work. The slope -0.77 ± 0.11 of ISSR length distribution observed in this study is comparable with the slope -1.66 ± 0.06 fitted for cirrus cloud length distribution in Wood and Field (2011)."

2) To address the spacing distribution, we also modify:

Line 383-389: "Besides the analyses on ISSR length scale, we also analyze the spacings between the ISSR segments and find them to be very small. The mean and median scales of the spacings are ∼47 km and ∼1 km, respectively. Similar to the fit of ISSR length, we apply a power law fit to the distribution of ISSR spacings (green dashed line in Fig. 6B). that is, log10(Number of events of spacing) = a + b × log10(Length of spacing). The intercept and slope of the fit are 3.5 ± 0.1 and -0.40 ± 0.03, respectively."

3) To address the relationship between RHimax and ISSR length, we also added clarification:

Line 398-404: "To examine whether the larger sized ISSRs correlate with larger or smaller RHi values, we calculated the mean RHimax value of all ISSRs within each size bin, as shown by the blue void triangles in Fig. 6B. The result shows that RHimax value increases with increasing ISSR length scale. We apply a linear fit (shown as blue dotted line in Fig. 6B) to the RHimax value versus the log scale ISSR length, that is, RHimax = a + b × log10(ISSR length). The intercept and slope of the fit are 64 ± 5 and 14 ± 1, respectively."

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Note that we also rewrote the Figure 6 legend in Line 957-972 accordingly.

Page 22263 line 25-end; aren't you missing just colder? (i.e., if an air mass is near or at saturation anyway, just dropping the temperature will produce supersaturation).

In Fig. 7 case 2 is defined as Tin < Tout and H2Oin $\leq$ H2Oout, theoretically. Yet in the real observations, it almost never happens that two horizontal segments of air have exactly the same value of H2O mixing ratio (i.e., H2Oin = H2Oout). Thus the case of "just colder" is included in the colder and drier situation (Tin < Tout and H2Oin < H2Oout) in observations. We added the clarification in the definition of three cases in Fig. 7 in Line 419-421: "We note although theoretically case 2 and case 3 include the situation of H2Oin = H2Oout and Tin = Tout, respectively, this situation almost never happens given the high precision of H2O and T measurements."

Page 22265, discussion of vertical velocity variations: I suggest deleting this discussion, unless you can provide good evidence that the variability in the vertical velocity measurements is accurate. Perhaps you can do that by looking at co-variability between temperature and w.

We agree with both reviewers' suggestion on deleting the discussion on vertical velocity variations given the uncertainties with these measurements. The original Fig. 10 and the discussion are therefore deleted, which includes the discussion of vertical velocity measurements in data and instrumentation, result and discussion.

Page 22269, end of page and start of next page: I don't follow the statement that turbulence contributes to the micro-scale structure of ISSRs, therefore water vapor spatial variability is the largest contributor to RHi spatial variability. Please explain in more detail.

We agree with the reviewer's comment and clarified that turbulence is only one possible cause of H2O spatial variability, yet more investigation is needed (Line 600-607): "For example, one possible cause of the microscale H2O spatial variability might be

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the widely observed turbulence in the troposphere (Gage and Nastrom, 1986; Nastrom and Gage, 1985; Nastrom et al., 1986). Yet we caution that high resolution measurements of 3-D wind fields are needed to fully understand the cause of microscale spatial variability of H2O field in the future."

Figure 14: I suggest adding a 4th panel to this plot, showing what the observed variation of H2O and T are that going into your RHi calculation, and also include an estimate of the uncertainty in the RHi calculation. Your max value appears to be less than 110%. Is that significantly different from 100%?

We revised Fig. 13 (original Fig. 14) in current manuscript by adding the times series of H2O, T into Fig. 13A. We note that the uncertainties in T, H2O measurements and in RHi values do not vary much throughout this example. Thus we only cited the uncertainty values in the text in Line 619-620 instead of adding the error bars in Fig. 13: "We note that for this example, the uncertainty in RHi is ∼13%." In addition, we also explained in Line 620-622: "Yet regardless of the uncertainties in RHi, the contribution of H2O variability to the variability of RHi would still be dominant even if all RHi values in this time series are lowered or increased by 13% altogether."

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Table 1. Data distribution and sampling range in this work

Data distribution	NH (0°-87°N)	SH (0°-67°S)	Tropics (30°S-30°N)	Extratropics (30°N-87°N, 30°S-67°S)
Flight hour of all T range (hr)	296.9	104.9	92.6	309.2
Flight hour of T ≤ -40°C (hr)	136.3	31	21.4	145.9
ISS observation (hr)	9.3	1.5	1.0	9.8
T (K) min; max	204.2; 311.0	195.9; 305.3	204.4; 311.0	195.9; 309.6
P (mb) min; max	133; 1023	133; 1039	134; 1024	133; 1039
H_2O (ppmv) min; max	1.87; 37500	1.45; 38900	2.41; 38900	1.45; 28900

Table 2. Contributions of H_2O and T horizontal variabilities to RH horizontal variabilities at various T, H_2O and P ranges

Bin by H_2O			Bin by T			Bin by P		
H_2O (ppmv)	$dRHi_q$	$dRHi_T$	T (°C)	$dRHi_q$	$dRHi_T$	P (hPa)	$dRHi_q$	$dRHi_T$
0 – 10	0.73	0.27	-80 – -60	0.88	0.12	0 – 200	0.90	0.097
10 – 30	0.89	0.11	-60 – -40	0.94	0.062	200 – 400	0.96	0.042
30 – 100	0.90	0.10	-40 – -20	0.98	0.024	400 – 600	0.97	0.027
100 – 1000	0.95	0.046	-20 – 0	0.97	0.035	600 – 800	0.96	0.041
> 1000	0.96	0.038	> 0	0.94	0.059	> 800	0.94	0.061

Fig. 1.

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Table 3. Contributions of H_2O and T horizontal variabilities to RH horizontal variabilities at various P ranges at different latitudes, over land and ocean and at different times of a year

	0 – 30°N		30°N – 60°N		60°N – 87°N		0 – 30°S		30°S – 60°S		60°S – 67°S	
P (hPa)	$dRHi_q$	$dRHi_T$	$dRHi_q$	$dRHi_T$	$dRHi_q$	$dRHi_T$	$dRHi_q$	$dRHi_T$	$dRHi_q$	$dRHi_T$	$dRHi_q$	$dRHi_T$
0 – 200	0.92	0.08	0.83	0.17	0.85	0.16	0.96	0.039	0.89	0.11	0.96	0.04
200 – 400	0.98	0.015	0.94	0.056	0.95	0.051	0.98	0.019	0.97	0.033	0.98	0.021
400 – 600	0.98	0.023	0.97	0.033	0.97	0.026	0.98	0.026	0.99	0.012	0.99	0.01
600 – 800	0.96	0.045	0.95	0.048	0.96	0.039	0.97	0.029	0.97	0.027	0.94	0.06
> 800	0.93	0.075	0.94	0.059	0.94	0.063	0.94	0.06	0.96	0.046	0.93	0.068

	Land		Ocean	
P (hPa)	$dRHi_q$	$dRHi_T$	$dRHi_q$	$dRHi_T$
0 – 200	0.83	0.17	0.94	0.066
200 – 400	0.94	0.059	0.98	0.023
400 – 600	0.96	0.045	0.98	0.017
600 – 800	0.94	0.057	0.97	0.033
> 800	0.94	0.063	0.94	0.059

	January (HIPPO1)		March (HIPPO2)		June (HIPPO3)		August (HIPPO4)		October (HIPPO5)		April-June (START08)	
P (hPa)	$dRHi_q$	$dRHi_T$	$dRHi_q$	$dRHi_T$	$dRHi_q$	$dRHi_T$	$dRHi_q$	$dRHi_T$	$dRHi_q$	$dRHi_T$	$dRHi_q$	$dRHi_T$
0 – 200	0.94	0.061	0.87	0.13	0.97	0.031	0.93	0.074	0.93	0.064	0.79	0.21
200 – 400	0.93	0.069	0.94	0.062	0.98	0.025	0.97	0.026	0.96	0.036	0.94	0.06
400 – 600	0.99	0.012	0.97	0.026	0.98	0.021	0.98	0.019	0.97	0.026	0.95	0.053
600 – 800	0.98	0.025	0.96	0.041	0.97	0.029	0.96	0.037	0.96	0.044	0.92	0.081
> 800	0.94	0.064	0.94	0.061	0.93	0.066	0.94	0.059	0.94	0.06	0.94	0.061

Fig. 2.

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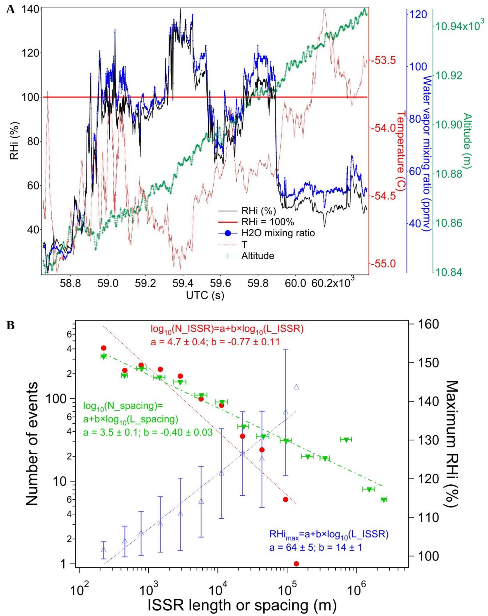

Fig. 3.

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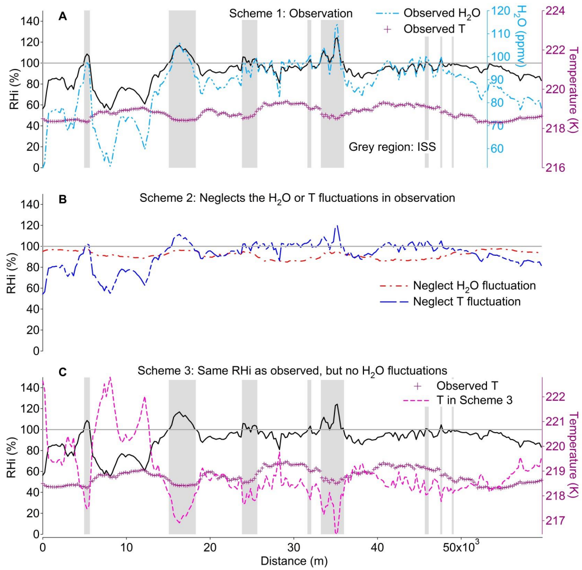

Fig. 4.

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