Dear Editor,
We thank two Reviewers for their useful comments and suggestions, which improved our manuscript. In the revised version of the manuscript we have carefully addressed Reviewers comments and suggestions. Our detailed replies are provided below.

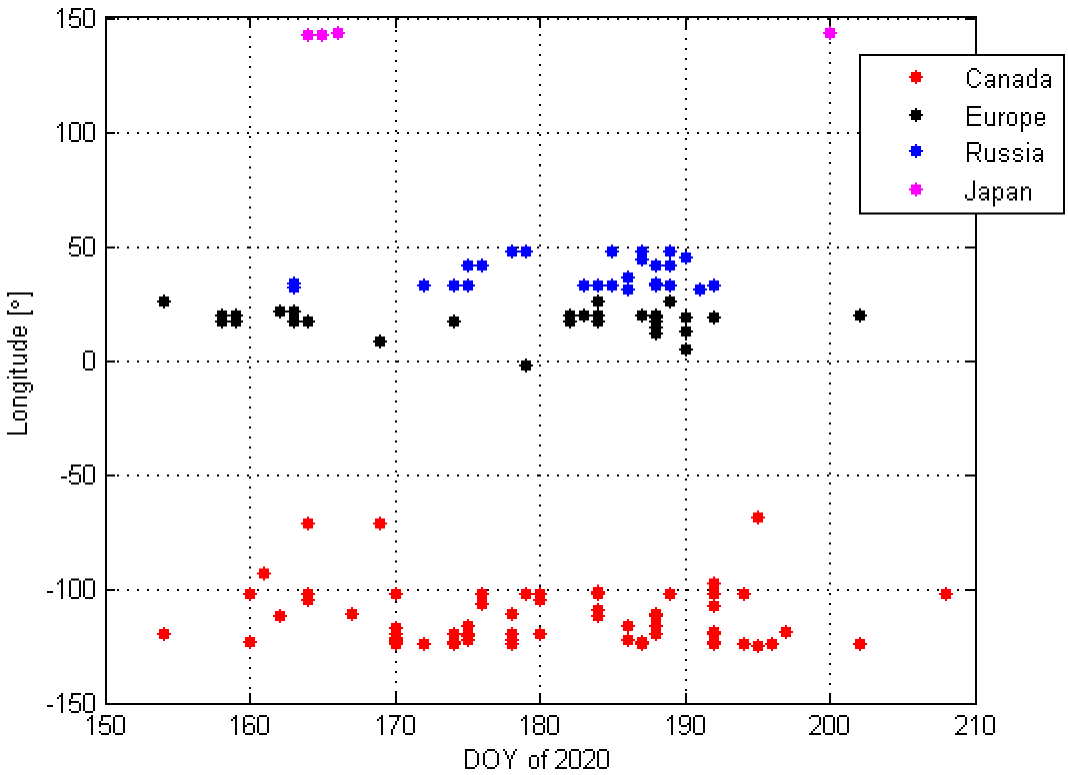
Reviewer 2:

The paper ñWhat caused the frequent and widespread occurrences of the noctilucent clouds at middle latitude in 2020?òby Dalin et al., examined ground-based NLC network data from Canada, western Europe and Russia for the unusual 2020 summer NLC season. Utilizing the zonal mean MLS temperature and water vapor measurements between 2005 and 2020, they found moderate temperature decrease in the mesopause region and significant increase of water vapor during summer of 2020. The correlation between solar activities and water vapor is not clear and the variability in solar activities canôt count for the increase of water vapor during the past few years. The satellite SO2 data were used as a proxy to water vapor changes induced by strong volcanic eruptions during 2013-2015. A strong correlation of ~0.5 was found with a 5-year lag for the aerosols to propagate into mid-to-high latitude mesopause region through meridional circulation. The authors conclude that the increase of the water vapor during 2017-2020 were caused mainly by the volcanic eruptions. This paper is well written and very easy to read. There are some concerns that should be addressed before publication.

In general, the authors focused on the year to year variability of NLC occurrence, mesospheric temperature and water vapor. Not much detail on their behaviors was given or discussed during this special 2020 NLC season.

1. It is nice that long-term data from 3 ground-based NLC observation networks are analyzed. The year-to-year variability is good for establishing the fact that 2020 summer NLC sighting reached maximum since 2005. However, it is not very clear what had happened during the 2020 summer NLC season other than that total number of NLC occurrence increased dramatically. It will be very helpful to get a better global picture if the authors can add a figure contains DOY and longitude of each events (total of 61) that occurred below 50N during the 2020 summer NLC season.

During the preparation of the manuscript I have produced such a picture shown below. As one can clearly see there is a strong inhomogeneous distribution of the points along the longitude due to a well understood reason: observational sites are highly concentrated in specific areas of Canada, Europe, Russia and Japan. It will be always like this. So it is simply impossible to extract any physical process from such a picture due to highly inhomogeneous point distribution. Such a picture will always confuse the reader and we want to avoid any confusion in this field. That is why we do not include this picture in our paper.



NLC occurrences as a function of longitude and time in 2020. Not for publication.

2. Consider adding the 2020 summer temperature and H2O time series to figure 1 to compare with 2009, the other active NLC season. Along with the above added figure, it will help relate the temperature/water vapor to NLC occurrences during the 2020 summer.

We agree with this comment and have added the 2020 summer temperature and H2O time series to Figure 1. It will indeed help the reader to compare the temperature/water vapor to NLC occurrences during two active periods in 2009 and 2020.

3. The ground-based NLC observations below 50N showed increased NLC activity during summer 2020 (Figure 3), it would be more logical/consistent to show the temperature and water vapor results in figure 9 and 11 using the 45-50 N latitude bin.

We agree with this comment and have shown the water vapor results in Figs. 9 and 11 using the 45-50 N latitude bin the revised manuscript. The results are the same as previous.

4. A moderate temperature decrease and significant increase of water vapor in the mesopause region are part of the main results. Thus, the authors focused on understanding the cause of the water vapor increase in this paper. However, as discussed in section 5 (page 20 and 21), though smaller, the observed temperature change has much larger impacts on the saturation ratio S than the observed water vapor increase. Discussions on why the temperature was colder

for 2020 were missing. Can the authors justify this, please? In the meantime, please use the temperature from Figure 5a to calculate their impact on the saturation ratio S. At 74 km, it is way too low in altitude (temperature too high) for the atmosphere to reach saturation for the NLCs to form.

Discussion about a possible temperature decrease and possible water vapor increase in 2020 have been added in the revised manuscript. In the revised manuscript, we have used the temperature from Fig.5a and water vapor from Fig.7a to estimate the impact on the saturation ratio at about 84 km altitude.

5. The authors discussed at length the dynamic factors that can affect the occurrence of NLC in the introduction and discussion by citing other people's previous published works when low latitude sightings of NLC occurred. The increases of planetary wave, tides and gravity wave activities played important roles for the enhanced NLC, especially for the lower latitude events. However, annual (summer), zonal mean MLS temperature and water vapor were used to examine their year to year variability. This approach won't be able to detect any planetary waves and tides. No further analysis was done to pursue this possible cause of the enhanced NLC activities. Is there colder region that corresponding to increase NLC sighting during the summer of 2020? Is it possible that planetary waves, tides and gravity waves played a role in the increased NLC sighting during summer 2020?

In the present paper, we consider annual (summer) zonal mean MLS temperature and water vapor measurements to examine their year to year variability at different altitudes and latitudes. This approach does not allow us to investigate activity of planetary, gravity waves and tides within a summer season and at a specific site. At the same time, it is well known that these wave processes experience an interannual (year-to-year) variability. For example, Huang et al. (2017) have demonstrated a clear interannual variability of the 6.5 planetary wave in the mesosphere. Sedlak et al. (2020) and Popov et al. (2020) have shown strong interannual changes in activity of long period gravity waves with periods of 3-11 hours. Nischal et al. (2019) have found interannual variability in amplitudes and phases of diurnal nonmigrating solar tides. Perminov et al. (2014) have found strong interannual variability in activity of both planetary and gravity waves in the mesopause region. Since all these wave oscillations induce variations in the mesospheric temperature, it is possible that it was an increased activity of those waves (or some of the waves) in the 2020 summer that resulted in lower temperatures that in turn leaded to the increased NLC sighting during the 2020 summer compared to the previous years. We have added this discussion in the revised manuscript.

6. The trends/changes in the mean temperature and H2O are discussed with different starting year, with temperature starting from 2016 and H2O from 2017 where there is a maximum or minimum. Please use the same starting year for both temperature and H2O when changes are discussed.

It is difficult to use the same starting year for both temperature and water vapor since their year-to-year variability is not exactly the same. That is why we use either 2016 or 2017 when it is appropriate.

Some minor points:

1. Please provide longitude ranges for the 3 NLC database.

We have added longitude ranges to the capture of Figure 3 for all four NLC databases used in the revised manuscript.

2. Line 178-184: is the Japanese data used in this paper for NLC occurrence other than here and in Figure 2? Is an example of NLC from one of the 3 datasets available?

No, the Japanese data were not used in the previous version of the paper. It is a good suggestion to add the Japanese NLC observations as a separate data set to Figure 3 since these automatic digital observations are rather long starting from 2010. The Japanese NLC observations are shown with the magenta line in Figure 3 of the revised manuscript.

3. Line 186-190: Please rephrase this sentence. It is hard to get to the point the first sentence of this paragraph trying to establish. Also, add country to Moscow in the bracket to be consistent with Edmonton and Hokkaido.

This sentence has been rephrased.

4. Line 338 and 492: in the mesopause region not ñatò

It has been corrected.

5. Line 525: I am not sure how can the authors ñemphasize that volcanic eruptions warm up the cold tropopause region that in turn facilitate a transfer of H2Oé ò. There is no evidence provided by this paper associated with ñwarmed up tropopause regionò during the past 5 years. Please consider remove this sentence or rephrase.

We disagree with this comment. It is well known that volcanic aerosols increase the tropopause temperature (see Randel el al., JGR, D02107, 2009, and references therein). The paper by Considine et al. (2001) carefully addresses this question (effects of the Mount Pinatibo eruption in 1991 on the tropopause and stratosphere), which clearly demonstrates both model and observational increase in H2O after the Pinatubo eruption in 1991. The authors concluded that ñ*The temperature of the model tropopause increases by ~0.5 K and results in a substantial transfer of H20 into the stratosphere across the model tropopause*.ò

We do not claim that ñé *with warmed up tropopause region during the past 5 years*.ò We just emphasis this important volcanic mechanism in our paper. We keep this sentence unchanged.

6. Line 536: remove one ñalsoò

One òalsoò has been removed.