Authors Response

Dear Reviewer,

we would like to thank you very much for your helpful comments and we included your comments in the revised version. The answers are given in *blue and italic* below each comment.

Yours sincerely,

Johannes Pletzer

Review of "The Climate Impact of Hypersonic Transport"
by Pletzer et al.

General Comments
The paper by Pletzer et al. provides a modeling study of the potential climate and ozone impacts due to emissions from Hypersonic Transport. The study is motivated by the growing contribution from aviation to climate change and also increasing desire to reduce air travel time. The present paper evaluated two hypersonic aircraft designs using two 3D chemistry-climate models, providing an assessment on climate and ozone impact for flying these aircraft. The present paper shows for the first time that a net chemical production at high altitudes leading to an increase of H2O perturbation lifetime and H2O concentration.

This is a very interesting and well-written paper that is a significant contribution that merits prompt publication. I only have a few minor suggestions for the authors to consider (below). What I find 'missing' is some contextual information. Also, I suggest that the limitations of the models need to be discussed more explicitly. I have detailed some of this below that might easily rectify this for the authors to consider.

Specific Comments
In the methods and simulations section, it is still not clear to me what nudging is applied in the models? I am assuming U wind, V wind and surface pressure? Is there anything else? Is it nudged all the way from surface to the model top? I assume the ERA-Interim meteorology fields first get interpolated to model grid (both horizontally and vertically) offline before nudged to the models? Please explain/clarify in the paper.

Thank you very much for this very positive feedback. We extended the information on the nudging setup with the following text:

"EMAC is based on the spectral transform dynamical core of ECHAM. The nudging is applied by Newtonian relaxation of the prognostic variables divergence, vorticity, temperature and the logarithm of the surface pressure in the spectral representation (spherical harmonics) of these variables towards the ECMWF ERA-5 reanalysis data . \textit{u} and \textit{v} wind are derived variables calculated through derivation and spectral transformation. The wave-0 of temperature (global mean) is omitted, there is further no nudging applied on the sub-synoptic scale, aiming at an optimal compromise between observed (i.e. reanalysed) and simulated meteorology.

Moreover, the nudging is applied in vertical direction only between the 4th model layer above the ground and approximately 200 hPa, in order to avoid inconsistencies in the planetary boundary layer and to let the stratosphere develop freely and driven by the tropospheric wave activity. This nudging setup is identical to that of the RC1SD-base-10 simulation described by \citet{Joeckel2016}. The ECMWF ERA-5 reanalysis data are preprocessed by spectral transformation and truncation for the applied model resolution."

The information that, first, only u and v wind components are nudged from 1000 hPa to 1 hPa in LMDZ-INCA was added to the text and, second, that the winds are interpolated on the horizontal grid in preparation of the run and are interpolated on the model pressure levels at each time steps.

L151
"The respective relaxation times are listed in 1."
The respective relaxation times are listed in Table 1?

The missing 'Table' was added.

L190 and L238
Two models seem to have large difference in derived lightning NOx – 0.2 TgN/yr and 5.5 TgN/yr in EMAC and LMDZ-INCA respectively. Why is that? How do these two models derived the lightning NOx. How does this large difference can potentially influence the results here, if any? Hope the authors could elaborate more on this.

We added further information on the parametrizations in the text. The Grewe parametrization in EMAC is based on convective mass-flux and in LMDZ-INCA on convective cloud heights. We added a comparison in the 'Simulations'-subsection. However, this is not where the difference comes from. The difference was actually an error in the selection of the correct variable. We corrected the lnox value from EMAC, which is 5.0 Tg and not 0.2 Tg. 5.0 Tg also agrees with Schumann and Huntrieser, who estimate the annual average lightning NOx production to be between 5 and 11 TgN/yr. V*alues of both models agree well with the range of the recent CMIP6 models: 3.2-7.6 TgN [Ref. IPCC AR6 chapter 6 (section 6.2.2.1)].*

L194
What are the vertical resolutions (especially in the upper troposphere and stratosphere) in the two models? What is the vertical resolution of the HIKARI aircraft emission inventory? What is the underline assumption of the aircraft emission spread throughout the model grid? What is the role of model diffusivity in the distribution of emissions? What is the limitation? More discussion on this aspect would be helpful.

The vertical resolution of EMAC in the applied T42L90MA resolution is approximately 550 m in the UTLS region, reaches 1200 m at the stratopause and increases to 3200 m in the mesosphere.

The vertical resolution of LMDZ-INCA in the applied resolution is approximately 1000-1300 m in the UTLS region, reaches 5000 m at the stratopause and increases to 8700 m in the mesosphere

We added information on the vertical resolution of both models and the horizontal and vertical resolution of HIKARI data.

Due to the rather coarse model resolutions of CCMs and CTMs (a sacrifice for the computationally expensive chemistry calculations) there is no horizontal diffusion, neither explicit nor parameterized, since the numerical diffusion of the applied large scale advection algorithm cannot be avoided. Vertical diffusion is parameterized for the vertical mixing in the planetary boundary layer.

L240 to L250
The model uses the meteorology data from the time period 2000-2014 to simulate climate impact in 2050-2064. One can argue that using the meteorology fields between 2000 to 2014 doesn't account for the dynamics changes (e.g., temperature and circulation) at the upper troposphere and lower stratosphere owning to climate change. For example, previous studies have shown that the Brewer–Dobson circulation has been strengthening in response to climate change (e.g., Butchart et al., 2006; Shepherd et al., 2011). How much difference can it make to the resulting effects?

Butchart, N., Scaife, A. A., Bourqui, M., De Grandpré, J., Hare, S. H. E., Kettleborough, J., ... & Sigmond, M. (2006). Simulations of anthropogenic change in the strength of the Brewer–Dobson circulation. *Climate Dynamics*, 27(7), 727-741. DOI 10.1007/s00382-006-0162-4

Shepherd, T. G., & McLandress, C. (2011). A robust mechanism for strengthening of the Brewer–Dobson circulation in response to climate change: Critical-layer control of subtropical wave breaking. *Journal of the Atmospheric Sciences*, 68(4), 784-797. https://doi.org/10.1175/2010JAS3608.1

Thank you for this comment. We added another subsubsection in the new discussion subsection 'Limitations of the Model Simulations'.

\subsubsection{Strengthening of the Brewer-Dobson Circulation}

In our model simulations we use atmospheric composition projections for the years 2050-2064 combined with present day meteorology (2000-2014). Hence, projections of the dynamic component are not included in our simulations. The main reason is, that reanalysis data from the future is simply not available for nudging. Using another method was not an option, since we rely on nudging to have the same meteorology in both models for a high signal-to-noise ratio. However, the changes of dynamic processes like the Brewer-Dobson circulation due to climate change are very likely significant and we therefore discuss the topic briefly \citep{butchart_simulations_2006,shepherd_robust_2011}. The associated transport is the dominant factor of water vapour perturbation lifetime and therefore of the climate impact of hypersonic aircraft. An increase in strength of the stratospheric and mesospheric circulation would most likely reduce the climate impact of hypersonic aircraft. \citet{butchart_simulations_2006} estimate the troposphere-stratosphere mean mass exchange rate to increase with 2 \% per decade (with considerabe differences between the models). That would result in an approximately 8-10 \% stronger circulation from 2050-2064 and in turn -- if the effect can really be directly translated to perturbation lifetime -- the climate impact of hypersonic aircraft would be reduced by approximately the same percentage, i.e. the water vapour perturbation lifetime and associated

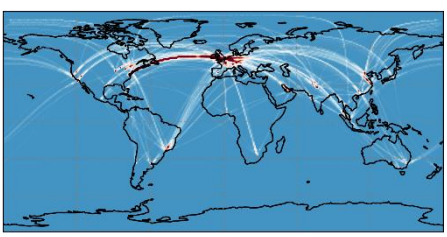
RF for the LAPCAT version calculated by EMAC might be reduced from 4.6 years and 40 mW/m2 to roughly 4.2 years and 36 mW/m2 when considering an enhanced Brewer-Dobson circulation.
.

Note: you should also add a few sentences about why you omitted the dynamical change (you had to!) because there are no "nudging" data available for the future, and the nudging was important for the signal-to-noise ratio … and it had to be "the same meteorology" in both cases for this … (thus, even if we would have nudged to dynamical data from a future EMAC simulation, eg. RCP-8.5 or similar, this would not have helped, since then the meteorological sequence is different and the signal-to-noise ratio goes down ...

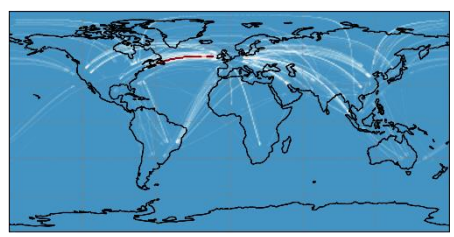
Figure 1 shows the vertical sum of H2O emissions over all vertical levels. How different the figure would be if one only plotted the emissions at cruise altitudes?

To our knowledge, potential hypersonic flight routes were identified in the HIKARI project. However, the city-pairs were not used in the 3 dimensional HIKARI data. The figure limited to e.g. stratospheric altitudes would therefore show very similar features like the vertical sum over all levels, excluding take-off and landing emission features in close proximity to the cities. We confirmed this with a world map plot, where only the stratospheric levels were integrated.

LAPCAT Emission Data



Integration over all vertical levels



Integration over selected vertical levels

We added the following sentence in the HIKARI section as additional information: 'All aircraft designs travel from and to the same city pairs'

L295
States that "Most of the emitted trace gases are transported to tropospheric altitudes". I am curious how much emitted H2O is chemically destroyed in the stratosphere? Have the authors explored the ratio of emitted stratospheric trace gases transported to tropospheric altitudes VS chemical destruction in the stratosphere? Which is the major contributor (transport or chemistry) to the stratospheric H2O sink here? It would be very interesting to see.

The major sink is transport to the troposphere. The chemical loss of water vapour is overcompensated due to the H_2O recombination and enhanced methane depletion (see table). Parts of the sentences might be misleading and are changed accordingly. Thank you for

pointing that out.

	Emission>18 km	Prod.	Loss	Loss to Troposphere
LAPCAT	13.7	4.77	-4.01	-14.46
ZEHST	21.2	14.64	-12.69	-23.15

'Most of the emitted trace gases are transported to tropospheric altitudes and only parts of the annual perturbation remain.' → 'During the fifteen years, the emitted trace gases, while being chemically converted, are continuously transported to tropospheric altitudes and only parts of the total emitted trace gases remain as changes to atmospheric composition.'

Table 3
It would be interesting to see how much percentage of total H2O perturbation stay in the atmosphere (above the tropopause) when it reaches equilibrium (e.g., Perturb. LAPCAT/ total LAPCAT emission *100% in two models)

We calculated how much of the annual H2O emission stays above the tropopause using the perturbation lifetime and the annual perturbation from Table 3. The ratio is listed in the following table.

Scenario	*EMAC*	*LMDZ-INCA*
ZEHST	*71.4 %*	*64.3 %*
LAPCAT	*78.3 %*	*76.2 %*

Table 4
shows that LMDZ-INCA calculates a higher ozone destruction than EMAC. The difference can be about 42% for lower flying aircraft (ZEHST). What factors can be mainly contributed to the difference derived in two models? Could the authors add a few sentences to discuss about this?

The main reason is the fact that EMAC produces an increase of ozone in the lower stratosphere. In terms of mass this is significant fraction of the total. Therefore the total loss is higher in LMDZ-INCA. We have to add that the caption was not up to date, since we present the relative total ozone changes, not the values above the tropopause, which we corrected.

L476
"over four year"
over 5 years? 2010-2014

Changed to 'over five years'.

A recent study by Zhang et al., 2021 calculated the stratospheric adjusted radiative forcing of water vapour and ozone perturbation at difference cruise altitudes. How does the water vapor and ozone radiative forcing impact in this study compared to their study? Scaling by per unit H2O emission in $mW(m^2Tg)^{-1}$?

Zhang, J., Wuebbles, D., Kinnison, D., & Baughcum, S. L. (2021). Stratospheric ozone and climate forcing sensitivity to cruise altitudes for fleets of potential supersonic transport aircraft. *Journal of Geophysical Research: Atmospheres*, 126(16), e2021JD034971. https://doi.org/10.1029/2021JD034971

To compare the results we used the pieces of information given in Zhang et al, which are fuel use, the H_2O emission index and radiative forcing for 19-21 and 21-23 km to calculate the linear relation and extrapolate this to cruise altitudes of the aircraft ZEHST and LAPCAT:

EI (H_2O) = 1,237 g H_2O/kg fuel burn
*→ 47.18 Tg Fuel → 47.18 Tg Fuel * 1.237 Tg H_2O / Tg Fuel = 58.36 Tg H_2O*

Radiative forcing
At 20 (19-21) km: 1.00 mWm^{-2} / Tg Fuel → 47.18 mW m^{-2}
At 22 (21-23) km: 1.12 mWm^{-2} / Tg Fuel → 53.1 mW m^{-2}

Linear Trend:

At 20 (19-21) km: 47.18 mW m^{-2} / 58.36 Tg H_2O → 0.81 mW m^{-2} / Tg H_2O
At 22 (21-23) km: → 53.1 mW m^{-2} / 58.36 Tg H_2O → 0.91 mW m^{-2} / Tg H_2O

Delta RF / delta km = (0.91 – 0.81) mW m^{-2} / Tg H_2O/ (23 – 21) km = 0.05 mW m^{-2}/ Tg H_2O / km

Extrapolation to 26 and 35 km:

*At 26 km: 0.91 mW m^{-2} / Tg H_2O + 0.05 mW m^{-2} / km * (26 – 22) km = 0.93 mW m^{-2}*
*At 35 km: 0.91 mW m^{-2} / Tg H_2O + 0.05 mW m^{-2} / km * (35 – 22) km = 1.56 mW m^{-2}*

We added a subsection on this topic (H_2O only) in the discussion.

\subsection{Comparison to Emission at Lower Altitudes}

\citet[Figure 11]{Zhang2021} published an altitude dependent comparison of ozone and water vapour RF normalized to fuel use. To compare their results on climate impact we used their emission index (EI(H$_2$O) = 1,237 g(H$_2$O)/kg fuel) and fuel use (47.18 Tg) to recalculate their results to RF per emitted water vapour in teragram. With the above values, we extracted the linear relation of 0.1 \unit{mW\,m^{-2} / 2 km} for an increase of RF with altitude. The extrapolation to ZEHST and LAPCAT cruise altitudes resulted in 0.93 \unit{mW\,m^{-2}} and 1.56

\unit{mW\,m^{-2}} for ZEHST and LAPCAT, respectively. Compared to our results (1.1-1.5 and 1.6-1.9 for ZEHST and LAPCAT, respectively), presented in Table \ref{table_rf}, the here calculated values are generally lower than EMAC results, especially compared to ZEHST. LMDZ-INCA results are lower for ZEHST compared to the extrapolation, however agree astonishingly well for LAPCAT. Clearly, the linear relation is not a perfect fit, however it shows the same trend and the order of magnitude agrees very well.

L563
"To conclude briefly, the impact on climate of aircraft emitting water vapour and flying above the tropopause increases very much with altitude." Agree with the authors: this conclusion is indeed valid for climate impact of water vapour emission with altitude; however, it might not be the case for ozone perturbation. Zhang et al study showed that there is an inflection point where the radiative forcing of ozone perturbation changes from positive to negative with increasing the flying altitude.

This is indeed true and an inversion point has been shown before in idealized simulations (not aircraft emission scenarios) by Lacis et al in "Radiative forcing of climate by changes in the vertical distribution of ozone". To clarify this topic, we extended the sentence.

'To conclude briefly, the impact on climate of aircraft emitting water vapour and flying above the tropopause increases very much with altitude, since water vapour radiative forcing is significantly larger than ozone radiative forcing, which has a more complex altitude dependency, and methane radiative forcing.'

In Kinnison et al. 2020 study, they have showed in figure 1 that the natural stratospheric photochemical production of water vapor resulting from the oxidation of methane is 60 Tg (H2O)/year, which seems to be much higher than the value (less than 14.6 Tg/yr) presented in Figure 7 and Figure 8 in this study. Could the authors explain a little why there is such a big difference?

60 Tg(H2O)/year should be the natural production in the model, shouldn't it? The values presented in Figure 7 and Figure 8 are the changes to the model's natural production (scenario-reference) and are therefore considerably smaller. To clarify, we added '(scenario-reference)' in both Figures.

The simulations assume an atmosphere without volcanic eruptions, but volcanic eruptions will happen in the time frame of an employment of hypersonic transport. What are possible effects of aerosol particles and water vapour of volcanic origin? How would this effect change the picture put forward here? Perhaps nothing can be said, but then this point should be clearer as a limitation of the study.

We added the following subsubsection in the discussion subsection 'Limitations of the Model Simulations':

\subsubsection{Aerosol and Water Vapour from Volcanic Origin}

In our model simulations, we assume an atmosphere without volcanic eruptions. However, volcanic eruptions could occur during the decades of operation of new aircraft. Volcanic emissions, like water vapour or sulphate aerosols, affect the atmospheric composition in the stratosphere, especially through heterogeneous chemistry, and these changes are strongly dependent on latitude and season. The changes of lower stratospheric water vapour changes due to volcanic eruptions is on the order of two years and affect ozone concentrations \citep{Stenke2005}. Sulfate aerosols are known to increase temperatures in the tropics and could in turn enhance the Brewer-Dobson circulation, eventually slightly reducing the climate impact of hypersonic transport. Overall, the topic is very complex in itself and how hypersonic emissions and volcanic emissions influence each other remains to be answered with robust and topic specific simulations.

L800
"over a time period 800 of fourteen years (2000-2014)"
over a time period 800 of fifteen years (2000-2014).

Added 'fifteen'.

L812
https://www.iagos.org/partners
The link doesn't work for me

Added a href with updated link '\href{https://www.iagos.org/organisation/members/}{IAGOS member institutions}'