Interactive comment on “Quantifying climate feedbacks in the middle atmosphere using WACCM” *by* Maartje Sanne Kuilman et al.

Anonymous Referee #2

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1 General Comments

The paper presents another application of CFRAM, a one-dimensional (mostly) radiative climate model for offline feedback analysis, in a more than a decade long series, now using output of the high top chemical climate model WACCM. In other studies it was used for example for a low top GCM (Taylor et al., 2013) or a CCM up to thermosphere (Zhu et al., 2016). When it was applied to global radiative models more than a decade ago, data transfer was straight forward but for use with complex 3D models it is essential to provide information on averaging of model output. I suppose CFRAM was applied for zonal averages at every meridional grid point and for every month of the 40 year time slices, am I right from hints only in the references? There are also a lot of other options. This has to be documented since this can contribute significantly to errors (see for example TEM-analysis mentioned by authors, line 652; Zhu et al., 2016).

First of all, the authors would like to thank the reviewer for the helpful comments.

The calculations are done at every grid point of the WACCM model after temporal means of the data of the perturbation run and the control run are taken. This means the data that go into the CFRAM calculations have the dimensions of latitude, longitude and height. A zonal mean has been done only after the calculations. This information has now been added to section 2.3:

We take the time mean of the WACCM data and perform the calculations for each grid point of the WACCM data. This means that in the end, we will have the temperature changes at each latitude, longitude and height.

The shown results are not new, they almost resemble what was found with chemical radiative convective models more than 30 years ago (e.g. Brühl and Crutzen, 1988). Concerning upper stratospheric ozone chemistry, the authors should for example read Cariolle (1983), what is written in the manuscript is a mess.

Thanks the references. The section on the changes in the ozone concentration due to the changed CO_2 concentration has now been rewritten and significantly shortened, as this is not new and not the main point of our work: we are interested in the temperature response as a result of the changes in the O_3 concentration in WACCM.

In general, the paper needs much more clear definitions what has been done.

It has been made clearer what has been done. Section 2.3 and 2.4 contain more information about on how the calculations are done.

2 Specific comments

The presented averages of temperature change from 12 to 80 km altitude in the abstract and also key points are confusing and not physically meaningful because several different regimes are involved. Here it would be more useful to focus on the upper stratosphere. Is the averaging mass weighted or not?

The authors agree it is better to show the temperature changes for the specific regions in the middle atmosphere. When calculating the temperature changes, we do take into account the mass of the layers as can be seen in equation (7). When doing the averaging over the different heights and latitudes, we take an ordinary average and do not account for this.

More than a decade ago is not recently (paragraph beginning with line 136). What is the spatially limited domain, please define. Provide references earlier. Merge with next paragraph and rearrange.

This has been done now.

The climate feedback-response analysis method (CFRAM) is an alternative method which takes into account that the climate change is not only determined by the energy balance at the top of the atmosphere, but is also influenced by the energy flow within the Earth's system itself (Cai and Lu, 2009, Lu and Cai, 2009). The method is based on the energy balance in an atmosphere-surface column. It solves the linearized infrared radiation transfer model for the individual energy flux perturbations. This makes it possible to calculate the partial temperature changes due to an external forcing and these internal feedbacks in the atmosphere. It has the unique feature of additivity, such that these partial temperature changes are linearly addable.

The paragraph beginning with line 157 is confusing concerning the statements on ozone here, skip that or define clearly what are the ozone changes due to, including the altitude dependence.

Right, this is how it is stated in their paper but we understand it misses more information here. As we don't want to do too much in detail of their study, this part has been removed.

In section 2.2 the assumptions for the other radiatively and chemically active gases should be provided. Is the double CO_2 scenario with preindustrial conditions for N_2O, CFCs, CH_4 and NOx in the troposphere? This is also critical for the SST.

This information has been added to section 2.2:

Other radiatively and chemically active gases, such as ozone, will change because of the changes in the CO_2-concentration, due to WACCM's chemical model as well.

As we used a fixed SST from the CSEM model as forcing. The atmosphere component of CESM is the same as WACCM, but does not include stratospheric chemistry. So you are right that this is an element that we are not including in our analysis.

Section 2.3 should include how WACCM output is implemented into CFRAM, i.e. the averaging methods for space and time.

This information has been added to section 2.3:

We take the time mean of the WACCM data and perform the calculations for each grid point of the WACCM data. This means that in the end, we will have the temperature changes at each latitude, longitude and height.

Split Fig. 2 and Fig. 4 into more vertical sections (e.g. lower stratosphere, upper stratosphere, mesosphere). What kind of averaging?

This has now been done: see Figure on the next page. The averaging procedure has also been explained in the text:

Figure 2 shows the average change in global mean temperature for the lower stratosphere, the upper stratosphere and the mesosphere for the experiment with the changed CO_2*-concentration and changed SSTs. To calculate the lower stratosphere temperature changes, we take the average value of the temperature change from the tropopause – the pressure level of which is an output of WACCM – until about 24 hPa for each latitude.*

The tropopause is not exactly at the same pressure level, we always take the one for the perturbation experiment which is a bit higher at some latitudes, to make sure that we don't use values from the troposphere. We add the values for each latitude up and take the average. This average is not mass weighted. The temperature changes in the upper stratosphere and in the mesosphere are calculated in the same way, but then for the altitudes 24 hPa-1 hPa and 1 hPa-0.01 hPa respectively.

Figure 2 shows the radiative feedbacks due to ozone, water vapour, clouds, albedo and the dynamical feedback, as well as the small contribution due to the Non-LTE processes, as calculated by CFRAM. The 'total'-column shows the temperature changes in WACCM, while the column 'error' shows the difference between temperature change in WACCM and the sum of the calculated temperature responses in CFRAM. In sections 3.3-3.6, we will discuss the different feedbacks separately in more detail, at this point we give an overview of the general effects and relative importance of the different feedback processes.

Figure 2 shows that the temperature change in the lower stratosphere due to the direct forcing of CO_2 *is around 3 K. We also observe that there is a cooling of about 1 K due to ozone feedback in the tropical region while there is a slight warming taking place in the summer hemispheres in both January and July. We also see that the temperature change in the lower stratosphere is influenced by the water vapour feedback and to a lesser degree by the cloud and albedo feedback.*

In the upper stratosphere, the cooling due to the direct forcing of CO_2 *is with about 9 degrees considerably stronger than in the lower stratosphere. The water vapour,* *cloud and albedo feedback play no role in the upper stratosphere and mesosphere. The ozone feedback results in the positive partial temperature changes, of about 2 K. This means that the ozone feedback yields a radiative feedback that mitigates the cooling, which is due to the direct forcing of* CO_2*. This has been suggested in earlier studies, such as Jonsson et al., 2004. With CFRAM, it is possible to quantify this effect and to compare it with the effects of other feedbacks in the middle atmosphere.*

The picture in the mesosphere is similar. The main difference is that the temperature changes are larger, note the difference of the range for the temperature change between Fig. 2c, d and Fig. 2e,f.

The temperature response due to dynamical feedbacks is small in global average. This can be understood as waves generally do not generate momentum and heat, but redistribute these instead (Zhu et al., 2016). However, the local responses to dynamical changes in the high latitudes are large, as we will see in section 3.3. There are some small temperature responses due to non-LTE effects as well.

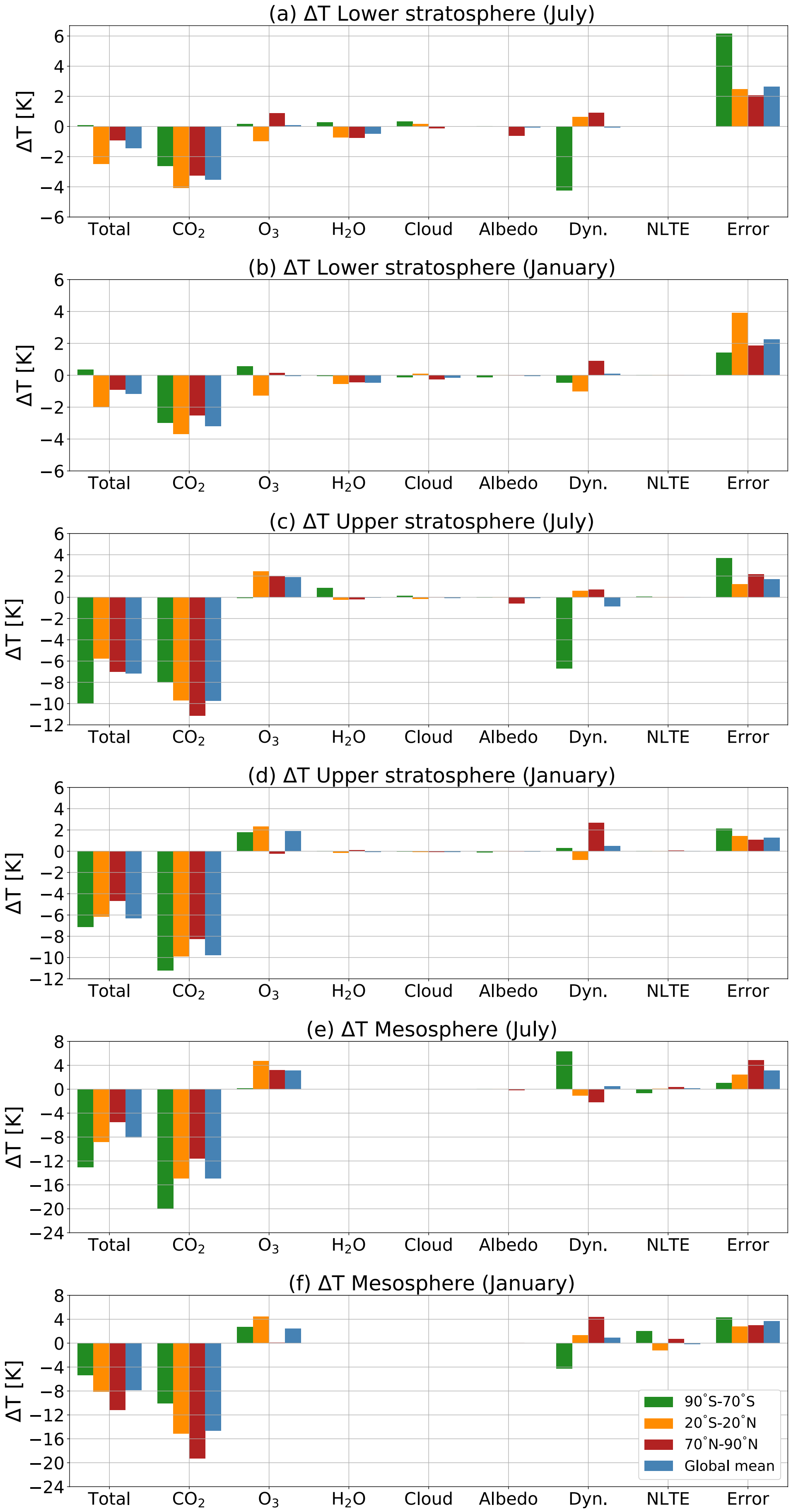
(a) ΔT Lower stratosphere (July)
ΔT [K]
6
4
2
0
−2
−4
−6
Total
CO_2
O_3
H_2O
Cloud
Albedo
Dyn.
NLTE
Error
(b) ΔT Lower stratosphere (January)
ΔT [K]
6
4
2
0
−2
−4
−6
Total
CO_2
O_3
H_2O
Cloud
Albedo
Dyn.
NLTE
Error
(c) ΔT Upper stratosphere (July)
ΔT [K]
6
4
2
0
−2
−4
−6
−8
−10
−12
Total
CO_2
O_3
H_2O
Cloud
Albedo
Dyn.
NLTE
Error
(d) ΔT Upper stratosphere (January)
ΔT [K]
6
4
2
0
−2
−4
−6
−8
−10
−12
Total
CO_2
O_3
H_2O
Cloud
Albedo
Dyn.
NLTE
Error
(e) ΔT Mesosphere (July)
ΔT [K]
8
4
0
−4
−8
−12
−16
−20
−24
Total
CO_2
O_3
H_2O
Cloud
Albedo
Dyn.
NLTE
Error
(f) ΔT Mesosphere (January)
ΔT [K]
8
4
0
−4
−8
−12
−16
−20
−24
Total
CO_2
O_3
H_2O
Cloud
Albedo
Dyn.
NLTE
Error
90˚S-70˚S
20˚S-20˚N
70˚N-90˚N
Global mean

Figure 2: The mean temperature responses to the changes in CO_2 and various feedback processes in the lower stratosphere from the tropopause height until 24 hPa (a,b), upper stratosphere from 24-1 hPa (c, d) and in the mesosphere from 1-0.01 hPa (e,f) in July (a, c, e) and January (b, d, f) in the polar regions (90°S-70°S and 70°N-90°N), the tropics (20°S-20°N) and the global mean, for experiment with double CO_2 and changed SSTs.

Figure 4 has also been changed:

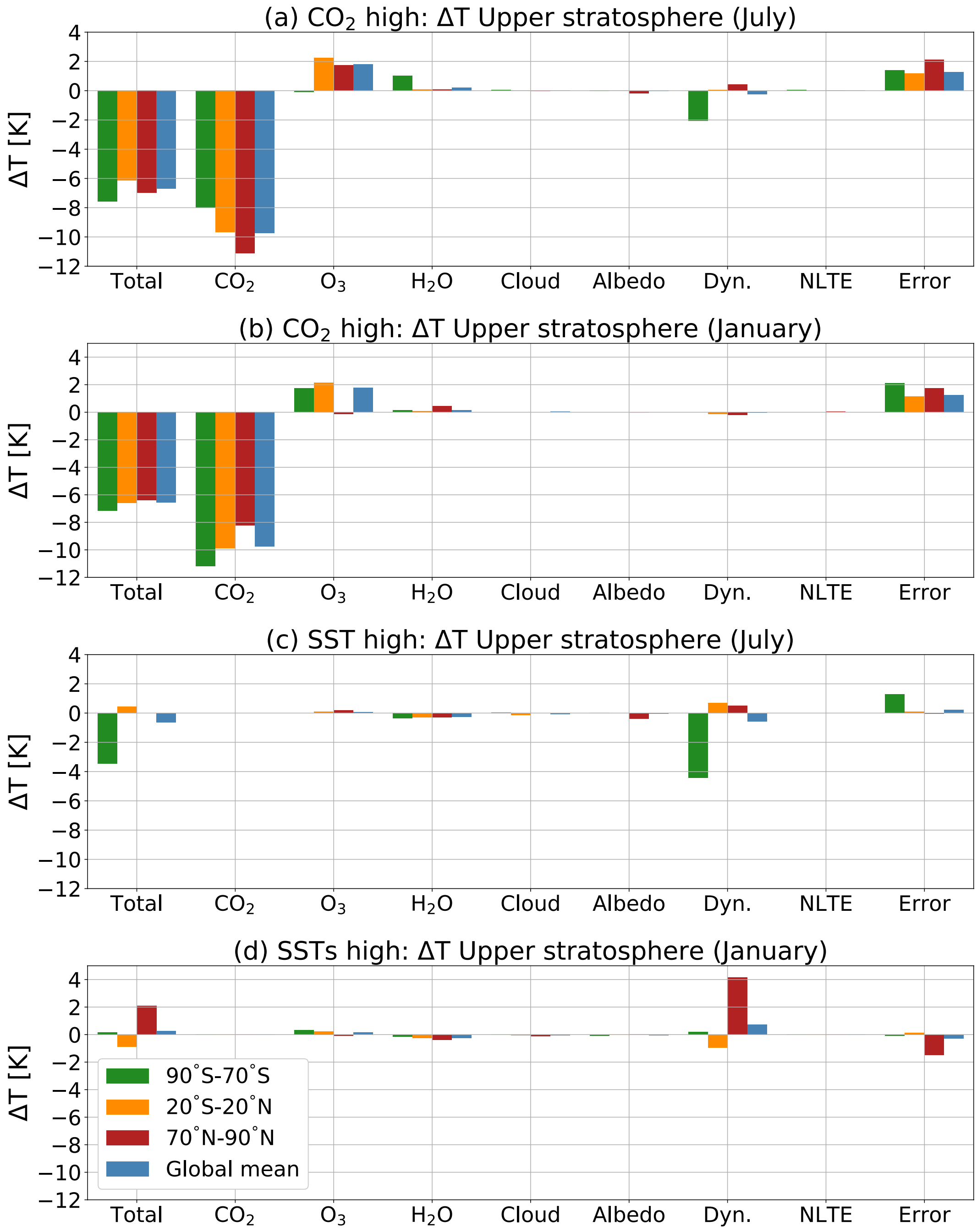

Figure 4: The mean temperature responses to the changes in CO_2 and various feedback processes in July (a,c) and January (b,d) in the upper stratosphere between 24 and 1 hPa, for polar regions (90°S-70°S and 70°N-90°N), the tropics

(20°S-20°N) and the global mean for the experiment with double CO_2 (a,b) and changed SSTs (c,d) separately.

Figure 4 shows temperature responses in the upper stratosphere for the experiment with double CO_2 (a,b) and changed SSTs (c,d) separately. These temperature changes were calculated as they were for Fig. 2. Again also, the 'total'-column shows the temperature changes as found by WACCM, the columns CO_2, O_3, H_2O, cloud, albedo, dynamics, Non-LTE shows the temperature responses as calculated by CFRAM. Error shows the difference between temperature change in WACCM and the sum of the calculated temperature responses in CFRAM.

We learn from this figure that the effects of the changed SSTs on the middle atmosphere are relatively small as compared to the effects of changing the CO_2. The changes in SSTs are responsible for large temperature changes as a result of the dynamical feedbacks especially in the winter hemispheres. A similar figure for the lower stratosphere (not shown) shows that the
the temperature response to the water vapour feedback is, however, almost solely due to changes in the SSTs.

Earlier, we discussed that the sum of the two separate temperature changes in the experiment with double CO_2 and changed SSTs is approximately equal to the changes observed in the combined simulation. We find that the same is true for the temperature responses to the different feedback processes.

The paragraph beginning with line 564 is confusing. I suppose you mean ozone changes induced by CO_2 cooling. Ozone matters also in the infrared window.

This was indeed what was meant, the paragraph has now been rewritten.

In addition, the vertical profile of the temperature responses to the direct forcing of CO2 and the feedbacks is shown in Figure 3. Here, one can see that the increase in CO_2 leads to a cooling over almost the whole middle atmosphere: an effect that increases with height. We also observe that in the summer upper mesosphere regions, the increased CO_2-concentration leads to a warming. The changes in ozone concentration in response to the doubling of CO_2 leads to warming almost everywhere in the atmosphere. In some places, this warming exceeds 5 K. In the polar winter the effect of ozone is small due to lack of sunlight.

Shorten the paragraph beginning with line 628.

This paragraph has now been shortened.

Changing the SSTs does not lead to a change in CO_2-concentration, therefore the temperature response to changes in CO_2 is not present for the run with only changed SST (Figures not shown).

You may improve the paragraph beginning with line 645 by the use of the textbook by Holton.

This section has been rewritten:

As discussed in the introduction, in the middle atmosphere there is a wave driven circulation which drives the temperatures away from radiative equilibrium. Large departures from this radiative equilibrium state are seen in the mesosphere and in the polar winter stratosphere. In the mesosphere, there is a zonal forcing which yields a summer to winter transport. In the polar winter stratosphere, there is a strong forcing that consists of rising motion in the tropics, poleward flow in the stratosphere and sinking motion in the middle and high latitudes. This circulation is referred to as the Brewer-Dobson circulation (Butchart et al. 2010).

Don't forget to mention convection around line 688.

This has now been mentioned.

The warmer sea surface temperatures enhance the activity of transient planetary waves and orographic gravity waves in the lower and middle stratosphere, for example via the amplification of deep convection (Deckert and Damaris, 2008). The changed SSTs also leads to enhanced dissipation of planetary waves, as well as orographic and non-orographic waves in the upper stratosphere.

Does Fig. 6 show the average of the 40yr time slice?

Yes, that is right. This is now mentioned explicitly in the text:

The differences in the meridional component of the residual circulation ($\bar{v}^*$) between the different simulations are shown in Fig. 6. These data are averaged over the 40 years of data.

Section 3.4 has to be rearranged and improved, the key processes are missing. The reaction $O+O_3$, the sink reaction in the Chapman chemistry, is strongly temperature dependent (see Brühl und Crutzen, 1988; Cariolle, 1983; or JPL). NO and Cl catalytic cycles matter mostly in the upper and mid stratosphere, in the mesosphere hydrogen species (e.g. OH) are most important. Check if in all calculations only CH_3Cl acts as chlorine source (pre-industrial!).

Thanks for this comment and the helpful references. The section on the changes in the ozone concentration due to the changed CO2 concentration has now been rewritten and significantly shortened, as this is not new and not the main point of our work: we are interested in the temperature response as a result of the changes in the O3 concentration in WACCM.

Ozone plays a major role in the chemical and radiative budget of the middle atmosphere. The ozone distribution in the mesosphere is maintained by a balance between transport processes and various catalytic cycles involving nitrogen oxides, HO_x and Cl_x radicals. In the upper stratosphere, NO_x and Cl_x cycles dominate (Cariolle, 1982), while OH is of utmost importance in the mesosphere (Jonsson et al., 2004).

In this paper, we are interested in the changes in ozone concentration induced by the increased CO_2 concentration and/or the changes in SST in WACCM. In the real *world, the ozone concentration is not only affected by the changing CO_2 concentration, but also by CFC and NO_x emissions.*

Fig. 8 shows the percentage changes in O_3-concentration when the CO_2-concentration and/or the SSTs change. An increase in CO_2, leads to an increase of ozone in most of the middle atmosphere. However, in the tropical lower stratosphere, the summer polar mesosphere, the winter and equatorial mesosphere, a decrease in ozone is seen. Fig. 8c and f show that changing the SSTs also has a significant impact on the ozone concentration. A complete account of the ozone changes is out of the scope of this paper, but the main processes responsible for ozone changes will be discussed.

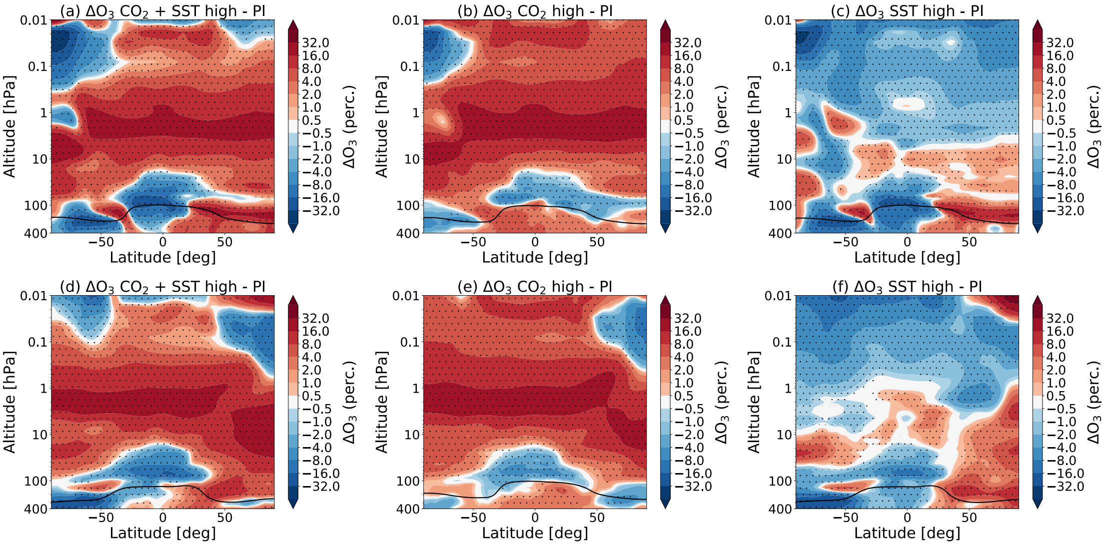

Figure 8: The percentage changes in ozone concentration in July (top) and January (bottom) for (a,d) the simulation with high CO2 and SSTs, (b,e) the simulation with high CO2, (c,f) the simulation with high SSTs, all as compared to the pre-industrial control simulation, as found by WACCM. The statistical signifance and tropopause height are indicated as in Fig. 6.

Ozone chemistry is complex, however the ozone increase between 30 - 70 km can be understood primarily as a result of the negative temperature dependence of the reaction $O + O_2 + M \rightarrow O_3 + M$. The fractional contribution of this processes and other loss cycles involving NO_x, CLO_x and NO_x varies with altitude.

At altitudes between 50 and 60 km, the ozone increase is understood by less effective HO_X odd oxygen destruction. The increase in O_3 between 45 and 50 km can be understood as the reaction rate coefficient of the sink reaction $O + O_3 \rightarrow 2O_2$ decreases. At altitudes lower than 45 km, there is a decrease of NOx abundance, which can explain the increase (Jonsson et al., 2004).

Schmidt et al. (2006) show that the decrease of ozone at the high latitudes in the summer mesosphere, is due to a decrease in atomic oxygen which results from increased upwelling. The decrease in O_3 concentration in the polar winter around 0.1 hPa is due to a stronger subsidence of NO and Cl, which are both ozone-destroying constituents.

The statement in line 820 is quite controversial, a lot of models lead to different results here; please check.

The caveat that all models don't consistently reproduce the tropopause temperatures has been added.

It can be seen that changing the SSTs leads to an increase in water vapour almost everywhere in the middle atmosphere (Fig. 10c and f). In WACCM, the increase in SSTs is observed to lead a higher and warmer tropopause, which can explain this increase of water vapour. However, it should be noted that models currently have a limited representation of the processes determining the distribution and variability of lower stratospheric water vapour. Minimum tropopause temperatures aren't consistently reproduced by climate models (Solomon et al., 2010; Riese et al., 2012). At the same time, observations are not completely clear about whether there is a persistent positive correlation between the SST and the stratospheric water vapour neither (Solomon et al., 2010).

Split the averaging region in line 903ff consistent with the new figures and the revised abstract.

The abstract and the conclusion have been revised.

4. Discussion and conclusions

In this study, we have applied the climate feedback response analysis method to climate sensitivity experiments performed by WACCM. We have examined the middle atmosphere response to CO_2 doubling with respect to the pre-industrial state. We also investigated the combined effect of doubling CO_2 and subsequent warming SSTs, as well as the effects of separately changing the CO_2 and the SSTs.

It was seen before that the sum of the two separate temperature changes in the experiment with only changed CO_2 and only changed SSTs is, at first approximation, equal to the changes observed in the combined simulation (see e.g. Fomichev et al. (2007) and Schmidt et al. (2006)). This is also the case for WACCM.

We have found that, even though changing the SSTs yields significant temperature changes over a large part of the middle atmosphere, the effects of the changed SSTs on the middle atmosphere are relatively small as compared to the effects of changing the CO_2 without changes in the SSTs.

We find that the temperature change due to the direct forcing of CO_2 increases with increasing height in the middle atmosphere. The temperature change in the lower stratosphere due to the direct forcing of CO_2 is around 3 K while in the upper stratosphere, the cooling due to the direct forcing of CO_2 is with about 9 K considerably stronger than in the lower stratosphere. In the mesosphere, the cooling due to the direct forcing of CO_2 is even stronger.

Ozone responds to changes in respond to changes in CO_2 and/or SSTs due to changes in chemical reaction rate constants and due to the strength of the up- and downwelling. The temperature changes caused by these changes in ozone *concentration generally mitigate the cooling caused by the direct forcing of* CO_2. *However, we have also seen in that in the tropical lower stratosphere and in some regions of the mesosphere, the ozone feedback cools these regions further.*

We also have seen that the global mean temperature response due to dynamical feedbacks is small, while the local responses to the changes in dynamics are large. Doubling the CO_2 *leads to a stronger summer-to-winter-pole flow, which leads to cooling of the summer mesosphere and a warming of the winter mesosphere. Changing the SSTs weakens this effect in the mesosphere, but leads to temperature changes in the stratosphere and lower mesosphere.*

The temperature change in the lower stratosphere is influenced by the water vapour feedback and to a lesser degree by the cloud and albedo feedback, while these feedbacks play no role in the upper stratosphere and the mesosphere.

It would also be interesting to investigate the exact mechanisms behind the feedback processes in more detail. Some processes can influence the different feedback processes, such as ozone depleting chemicals influencing the ozone concentration and thereby the temperature response of this feedback. Other studies have shown that a surface albedo change, which is associated with sea ice loss, can influence the middle atmosphere dynamics, which in turn influences the temperature response (Jaiser et al., 2013). The CFRAM cannot unravel the effects of these different processes.

There is also a need for a better understanding of how different feedbacks in the middle atmosphere affect the surface climate. As discussed in the introduction, the exact importance of ozone feedback is currently not clear While this paper focused on the temperature changes in the middle atmosphere, similar analysis can be done to quantify the effects of feedbacks on the surface climate.

In conclusion, we have seen that CFRAM is an efficient method to quantify climate feedbacks in the middle atmosphere, although there is a relatively large error due to the linearization in the model. The CFRAM allows for separating and estimating the temperature responses due an external forcing and various climate feedbacks, such as ozone, water vapour, cloud, albedo and dynamical feedbacks. More research into the exact mechanisms of these feedbacks could help us to understand the temperature response of the middle atmosphere and their effects on the surface and tropospheric climate better.

3 Technical corrections

Please define all formula letters in line 298.

This has now been done:

$$\Delta(\vec{S}-\vec{R}) = \Delta(\vec{S}-\vec{R})_{(WACCM)} \; * \; mass_k \; * \; c_p \qquad (5)$$

In which $\Delta(\vec{S}-\vec{R})$ is the difference in the shortwave radiation $\overrightarrow{(S)}$ and longwave radiation $\overrightarrow{(R)})$ between the perturbation run and the control run as a flux in Wm^{-2}, while $\Delta(\vec{S}-\vec{R})_{(WACCM)}$ is this difference as heating rate in Ks^{-1} in WACCM, with $mass_k = \frac{p_{k+1} - p_k}{g}$ with p in Pa and $c_p = 1004$ J kg^{-1} K^{-1} the specific heat capacity at constant pressure.

In line 546 something is missing or twice. Right, this has been corrected.

Add 'high latitude' in line 616. This has been added.

Typo in line 688. This has been corrected.

Captions of Fig. 7 to 11 can be shortened (tropopause as in Fig. 6).

Thanks for this comment, this has been implemented now.

4 References

Brühl, C. and P.J. Crutzen: Scenarios of possible changes in atmospheric temperatures and ozone concentrations due to man's activities, estimated with a one-dimensional coupled photochemical climate model. Climate Dynamics, 2: 173-203, 1988.

Cariolle, D.: The ozone budget in the stratosphere: results of a one-dimensional photochemical model. Planet. Space Sci., 31: 1033-1052, 1983.

Others see discussion paper.