We thank Susan Solomon for the detailed review of our manuscript and the suggestions. Below we provide a point by point reply with Prof. Solomon's comments in italics and our answers in normal font.

The paper uses ERA interim reanalysis and a suite of models to probe Arctic temperature trends for the past and future. The subject is timely especially given the cold arctic winter of 2011. I think the paper should merit publication after a revision, but have several significant concerns as well as minor issues that should be addressed in revision.

1. Despite the interesting paper by Thompson that is referenced, I still feel that using reanalysis for trends is subject to question. Particularly since the paper attempts to deduce dynamical and radiative contributions by difference, absolute accuracy needs to be very high for this method to work well. A section should be added on how large the uncertainties in eddy heat flux are estimated to be, and how these propagate into the rest of the calculations.

2. How do ERA interim temperature trends compare to MERRA? I am concerned about the error estimates, but a check with another reanalysis would help.

As also suggested by Anonymous Referee #1, we have now included calculated temperature trends from the RICH adjusted radiosonde data set (Haimberger et al., 2012). Fig. 1 (see below) is an update of Fig. 1 of our manuscript now including trends based on RICH and also trends based on MERRA. Both re-analyses data sets agree very well with each other and also agree generally very well with the RICH temperature trends.

Fig .2 shows that the heat flux trends from MERRA and ERA-Interim agree very well, with differences between the two reanalyses much smaller than the statistical error. While we cannot reasonably estimate the systematic errors in heat fluxes and heat flux trends, the good agreement between ERA interim and MERRA gives confidence that the results based on the heat flux trends are robust. Consequently, results for the inferred dynamical and radiative trends (Fig. 1b-c) agree well between ERA Interim and MERRA.

In our revised manuscript we will include observations from RICH in the revised Fig. 1 as shown below, and in Table 2 of our manuscript and will also include MERRA in the revised Figs. 1 and 2 and Table 2.

3. How sensitive are the results to the assumed 45 day window? What if it were 30 or 60? Is the radiative damping time temperature/season dependent?

The results are not very sensitive for the radiative damping time applied. We tested various damping times between 30 and 60 days and obtained very similar results for the radiative temperature trends with the highest correlation between heat flux and temperature anomalies for a 45 day window. The 45 days are consistent with the results of Newman and Rosenfield (1997) for high latitude winter/spring. During summer, radiative damping times will be shorter; however, dynamics have a much smaller impact during summer and our calculated radiative temperature trends during summer are largely insensitive to the radiative damping time assumed. A comment on this will be included in our revised manuscript.

4. Why were radiative terms described as a linear regression? If as seems likely much of the radiative cooling to date is due to ozone loss (especially in spring), then a fit to EESC may describe it better than a linear trend alone. How much difference would an EESC fit make to your estimates?

We prefer to use linear regression throughout our study. Ozone loss has certainly contributed to the past temperature trends. Indeed we find from our EMAC calculations and from the CCMVal-2 models that future temperature trends will be smaller than past temperature trends, which is likely at least partly due to the recovery of ozone. However, our EMAC calculations and most of the CCMVal-2 models show a continued cooling of the Arctic lower stratosphere in the future; temperature changes from the past into the future can therefore not reasonably well be described by an EESC-like function alone. In fact our sensitivity calculations with fixed CO_2 (or other well mixed greenhouse gases) versus fixed ODS show only a minor effect for fixed ODS while most of the future temperature trends is due to changes in CO_2 and other well mixed greenhouse gases.

5. It is curious that the summer season radiative model values are so far off of the observations. This seems difficult to understand unless the ozone depletion is wrong, or there is another kind of *shortcoming. Please compare the models' ozone losses to the ozone observations of Randel and Wu, and please discuss implications of both ozone loss and temperature discrepancies.*

We have now compared Arctic ozone trends from our EMAC standard simulation and the CCMVal-2 models with the trends calculated from observations by Randel and Wu (2007). Figs. 3 and 4 below show ozone trends at 50hPa averaged over 60°–90°N f or 1979 – 2005 (period chosen to allow a direct comparison with the Randel and Wu data) and 2000 – 2049. While the shape of the ozone trends is similar between the models and the observed trend with maximum losses in spring and smallest losses in summer/autumn, the models underestimate the observed trends. In any case, there is a large scatter between different models. However, it should be noted that the lower stratospheric ozone trends poleward of 60°N in the Randel and Wu (2007) data set are based on only a single ozone sonde station and are thus itself subject to considerable systematic uncertainty.

We will include the ozone trends (Figs. 3 and 4) together with a corresponding discussion in our revised revised manuscript.

6. I assume you analyzed the models in the same manner as you did the observations. Please state this. Also, what about looking at the modeled change in the residual mean vertical velocity, as a consistency check on the dynamical contribution?

Yes, the models were analysed in the same way as the reanalyses, using regression with the 100hPa eddy heat flux. A comment on this will be included in the revised manuscript. We also tested regression with 50hPa residual vertical velocities over 60-90°N for some cases and obtained similar results as for regression with 100hPa eddy heat flux over 45-75°N. In order to be consistent with the trend calculation with the reanalyses we focus on 100hPa heat flux in this study.

7. What is the definition of 'arctic' used? I assume 65N to 90N throughout, although I think this is only stated in the conclusion section. Do you think you might get better agreement by defining a vortex edge using PV, and averaging over the vortex?

Throughout our manuscript we use 60°–90°N as Arctic . We will state this more clearly in the revised manuscript. Use of a vortex average (e.g., as defined by potential vorticity) instead is problematic for at least two reasons: (a) this information is not easily available for the CCMVal-2 models and (b) even more importantly, there is no similar theoretical framework to relate eddy heat fluxes with temperature changes in PV coordinates. Thus we will concentrate on polar cap (60°–90°N) averages here.

8. Is a general conclusion of this paper that radiative cooling will offset about 15% of the ozone recovery in coming decades? If so, please state this; if not, what is the bottom line?

Thank you for the suggestion to make this point clearer. The possible effect of Arctic stratospheric cooling on ozone recovery is indeed the main motivation for our study here. Sinnhuber et al. (2011) calculated that a cooling of the Arctic winter stratosphere by about 0.8 K/decade could fully offset expected Arctic ozone recovery. The observed radiatively induced cooling of the Arctic winter stratosphere over the past decades by about 0.5 K/decade could thus offset more than 50% of the expected Arctic ozone recovery if continuing into the future. However, the model projections indicate that future cooling will be reduced by about 40% compared to cooling over the past decades. Based on the observed cooling and the projected reduction in the rate of cooling from the model calculations we would arrive at a projected radiatively induced cooling of about 0.3 k/decade which would be sufficient to offset 30-40% of the expected ozone recovery. Projected cooling from the CCMVal-2 models itself is smaller than this value, with cooling ranging from 0.1 K/decade for the annual mean to 0.17K/decade for DJF. This would correspond to offsetting between about 15 to 20% of the expected ozone recovery. In this sense the projected radiatively induced cooling could offset between about 15 and 40% of the expected Arctic ozone recovery, substantially delaying recovery. Will state this in the conclusions of our revised manuscript.

9. Why is the EMAC radiative cooling so strong in SON (seen in both figs 4 and 5). I can't think of a reason this would occur radiatively, and it seems strange that this occurs in both past and future. Please explain.

We cannot give a simple answer as to why future radiative cooling trends will be stronger during SON than JJA, but we note that this is also the case in the CCMVal-2 multi model mean. However, this is not the case for the past as seen in Table 2 (for the past, the multi model mean has a smaller SON trend than JJA, while in EMAC SON and JJA are practically identical within the statistical errors). A discussion of this will be included in our revised manuscript.

10. Are water vapor changes playing any role in EMAC? What about the other models?

The model calculations exhibit an increase in stratospheric water due to the increase in methane and possibly also changes in the transport of water into the stratosphere. However, trends in water vapour vary considerably between different models and it is possible that this contributes to differences in temperature trends between different models. However, we have not investigated this in detail here.

11. I would expect the radiative tests in figure 5 to be linearly additive, except for ODS. I don't understand why the different EMAC tests show such widely varying responses by gas and season. Can you explain? Are you confident that this is not due to low S/N due to high variability in the Arctic, in which case many more runs would be needed to get meaningful answers?

The global means for the sensitivity runs shown in our Table 3 are linearly additive within the statistical uncertainties: constant CO_2 reduces cooling by 0.20 K/decade from -0.30 K/decade in the standard run to -0.10 K/decade, constant N_2O reduces the cooling by 0.02 K/decade and constant CH_4 by 0.06 K/decade. Together this amounts to a reduction of 0.28 K/decade, which agrees within the statistical errors with the reduction of 0.24 K/decade for the case with all three gases fixed. However, for the Arctic (Fig. 5) the large internal variability makes most of the results not statistically significant.

Minor points
Abstract, line 23. Observations can confirm models, but not the reverse since models are not data, and can also be right for wrong reasons.

Okay, thanks. Will be changed.

Table 2. Are these errors purely statistical? Please say so, and note the possibility of structural uncertainties in the text.

Yes, all errors shown are purely statistical. We will state this more clearly in the revised manuscript and also note the possibility of additional systematic uncertainties.

Additional references

Haimberger, L., Tavolato, C., and Sperka, S., Homogenization of the global radiosonde temperature dataset through combined comparison with reanalysis background series and neighbouring stations, J. Clim., 25, 8108-8131, 2012.

Newman, P. A. and Rosenfield, J. E., Stratospheric thermal damping times, Geophys. Res. Lett., 24, 433–436, 1997.

Randel, W. J. and Wu, F., A stratospheric ozone profile data set for 1979 – 2005: Variability, trends and comparisons with column ozone data, J. Geophys. Res., 112, doi:10.1029/2006JD007339, 2007.

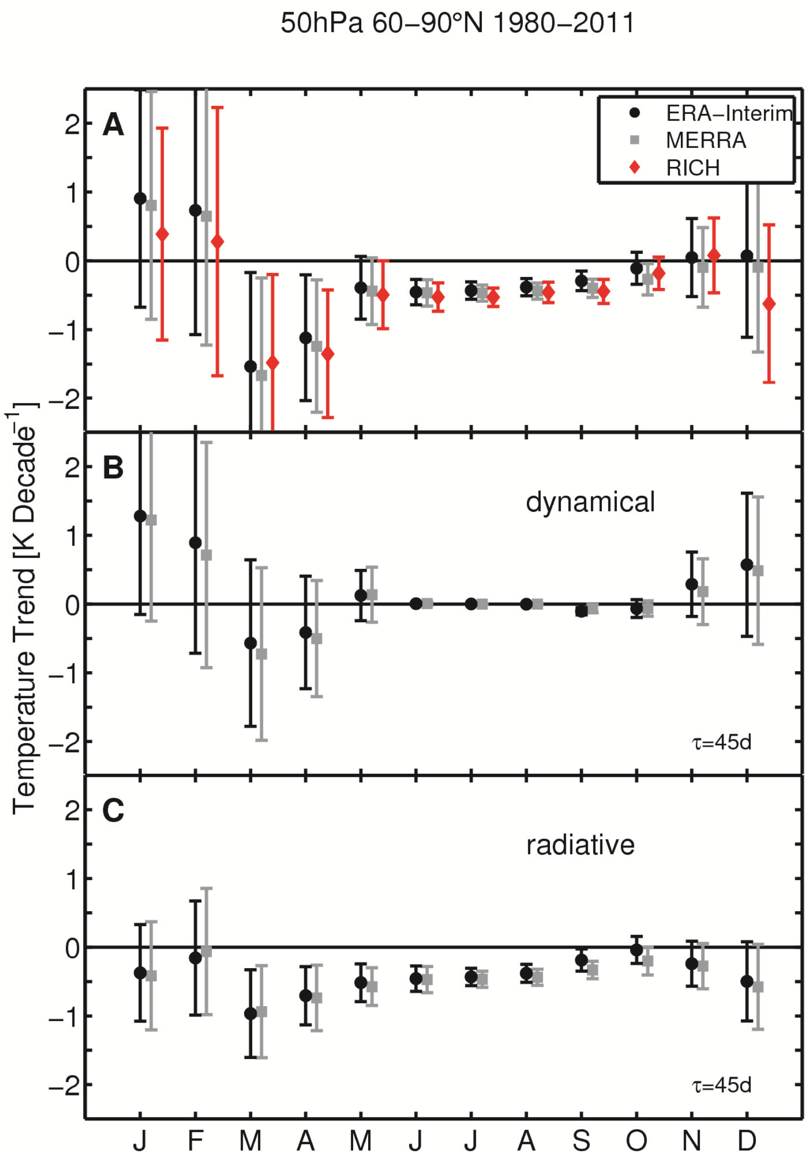

Fig .1. Arctic (60°-90°N) temperature trends at 50 hPa fro m ERA-Interim (black), MERRA (gray) and RICH adjusted radiosonde observations (red).

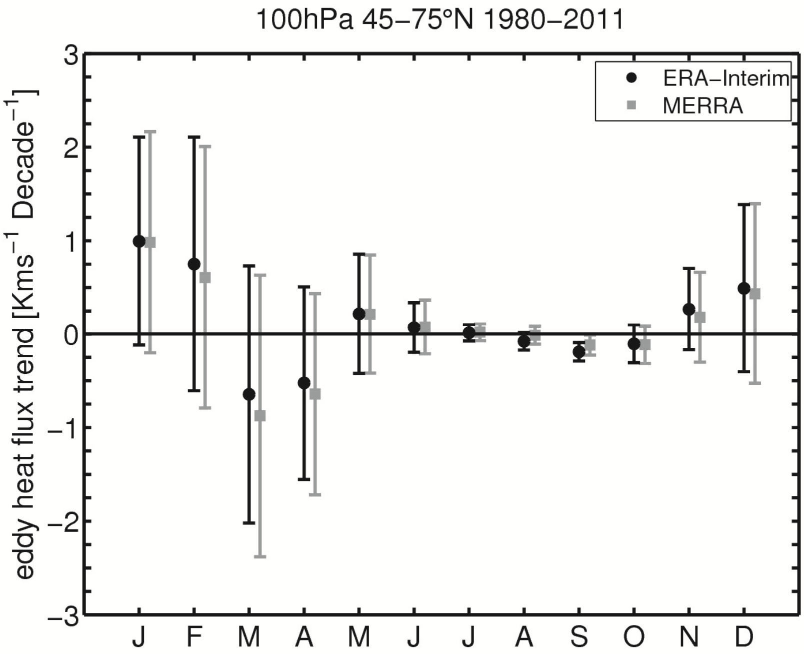

Fig. 2. 100 hPa eddy heat flux from ERA Interim (black) and MERRA (gray) averaged over 45°-75°N.

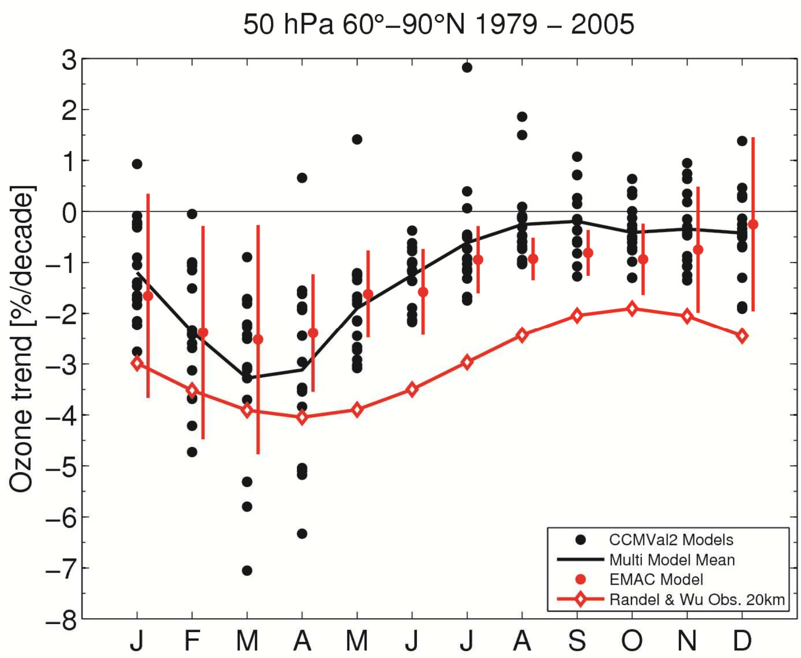

Fig. 3. Arctic (60°-90°N) ozone trends at 50 hPa between 1 979 and 2005 from 16 CCMVal-2 model (black dots), EMAC model (red dots with error bars) and observed ozone trends from Randel and Wu (2007) at 20km red line with diamonds).

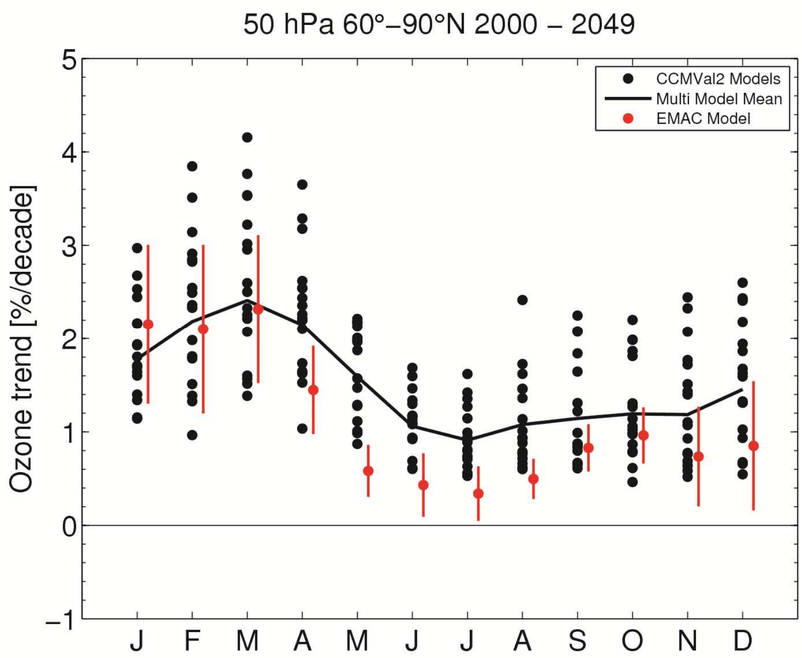

Fig. 4. As Fig. 3 but for the period 2000 – 2049.