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LETTER

The contribution of greenhouse gases to the recent slowdown in global-mean temperature trends

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Abstract

The recent slowdown in the rate of increase in global-mean surface temperature (GMST) has generated extensive discussion, but little attention has been given to the contribution of time-varying trends in greenhouse gas concentrations. We use a simple model approach to quantify this contribution. Between 1985 and 2003, greenhouse gases (including well-mixed greenhouse gases, tropospheric and stratospheric ozone, and stratospheric water vapour from methane oxidation) caused a reduction in GMST trend of around 0.03–0.05 K decade^{-1} which is around 18%–25% of the observed trend over that period. The main contributors to this reduction are the rapid change in the growth rates of ozone-depleting gases (with this contribution slightly opposed by stratospheric ozone depletion itself) and the weakening in growth rates of methane and tropospheric ozone radiative forcing. Although CO_2 is the dominant greenhouse gas contributor to GMST trends, the continued increase in CO_2 concentrations offsets only about 30% of the simulated trend reduction due to these other contributors. These results emphasize that trends in non-CO_2 greenhouse gas concentrations can make significant positive and negative contributions to changes in the rate of warming, and that they need to be considered more closely in analyses of the causes of such variations.

1. Introduction

There has been extensive discussion of the nature, causes and even the very existence of the slowdown in the rate of global warming between the late 1990s and around 2010 (e.g. Karl *et al* 2015, Marotzke and Forster 2015, Trenberth 2015, Fyfe *et al* 2016). In the discussions of the slowdown, there has been surprisingly little attention given to the role of greenhouse gases, which are the principal component of human-induced climate change (IPCC 2013a).

Myhre *et al* (2013) (see especially their figure 8.6, also Hansen and Sato (2004) and Montzka *et al* (2011)) show that the rate of change in the radiative forcing (RF) from well-mixed greenhouse gases (WMGHGs—CO_2, methane, nitrous oxide, and ozone-depleting and other fluorinated species) decreased from 1980s values of about 0.04 W m^{-2} yr^{-1} to around 0.03 W m^{-2} yr^{-1} in the following two decades, but they did not discuss the impact of this on temperature.

The reduced trend resulted mostly from the stabilisation and then decrease in concentrations of ozone-depleting substances (ODSs) (notably chlorofluorocarbons) as a result of the emission controls by the Montreal Protocol (see also Velders *et al* 2007). The reduced growth rate of methane (e.g. Hartmann *et al* 2013, Dalsøren *et al* 2016) as a result of both changes in emissions and methane lifetime also contribute.

Estrada *et al* (2013) used statistical techniques to highlight the possible role of ODSs (and, to a lesser extent, methane) on the recent slowdown. Their focus was on the impact on RF; the impact on temperature was not directly quantified, but was inferred from similarities in the time series, by identifying common break-points (i.e. times when significant changes in trends occur). Pretis and Allen (2013), in a critique of Estrada *et al* (2013), used a simple climate model to quantify the potential role of ODSs on global-mean surface temperatures (GMST); they found that temperatures would have been around 0.1 K higher in

2013 had the ODS RF grown linearly since 1990, instead of following the observed path (see also Xu *et al* 2013). They also noted that the effect of the slower growth rate of methane on temperatures was 'much smaller' but did not quantify this.

Recently Smith *et al* (2016), in a study of the role of aerosols on the GMST slowdown, showed an analysis of CMIP5 Earth-system model integrations driven only by WMGHG forcing. The smoothed GMST trends peaked at about 0.3 K decade^{-1} in about 1980, and fell to about 0.22 K decade^{-1} by the late 1990s, before slowly increasing. Given that the observed GMST trend is around 0.2 K decade^{-1}, the WMGHG-driven changes are clearly an appreciable fraction of the trend. The available CMIP5 integrations did not isolate the effect of individual WMGHGs in driving the slowdown. In addition, the analysis of Forster *et al* (2013) indicates a considerable diversity in the inferred WMGHG RF amongst CMIP5 models, with a 5%–95% uncertainty range in the year 2003 forcing of 1.6 W m^{-2} (and a total range of almost 2 W m^{-2}), which can be compared to the 1.1 W m^{-2} range assessed by Myhre *et al* (2013). Figure 3(a) of Forster *et al* (2013) also shows considerable diversity in the time dependence of the WMGHG forcing amongst the models. Such diversity would affect the derived impact of WMGHGs on GMST trends from this set of models.

This letter provides an assessment of individual greenhouse gas drivers of GMST trends using a simple climate model approach; this can provide a deterministic assessment which would not be possible in more complex global climate models, where the signal would be masked by unforced variability. The simple model also allows the parameter space of uncertainty in, for example, climate sensitivity, to be explored more easily. In addition to the WMGHGs, we include the variations in RF due to other greenhouse gases, notably stratospheric ozone, as its RF is principally driven by ODS trends (and, to some extent, offsets the direct climate role of ODSs), stratospheric water vapour changes due to methane oxidation, and tropospheric ozone. We refer to these collectively as GHGs. Hartmann *et al* (2013) report that tropospheric ozone concentrations have likely levelled off or decreased in Europe and North America, and increased in East Asia since 1990, with a resulting slowdown in the global trend in RF (Myhre *et al* 2013). As noted by Myhre *et al* (2013) the confidence in the tropospheric and stratospheric ozone RF is lower than that of the WMGHGs ('high' as opposed to 'very high'), because of uncertainties in both the observed trends, and in the RF resulting from those trends. The confidence level in methane-induced stratospheric water vapour trends is given as 'medium'.

The paper is structured with two main sections, one indicating the methodologies and datasets used here, and the other describing the main results. The main conclusions are then summarised. Additional results and data are provided in supplementary data.
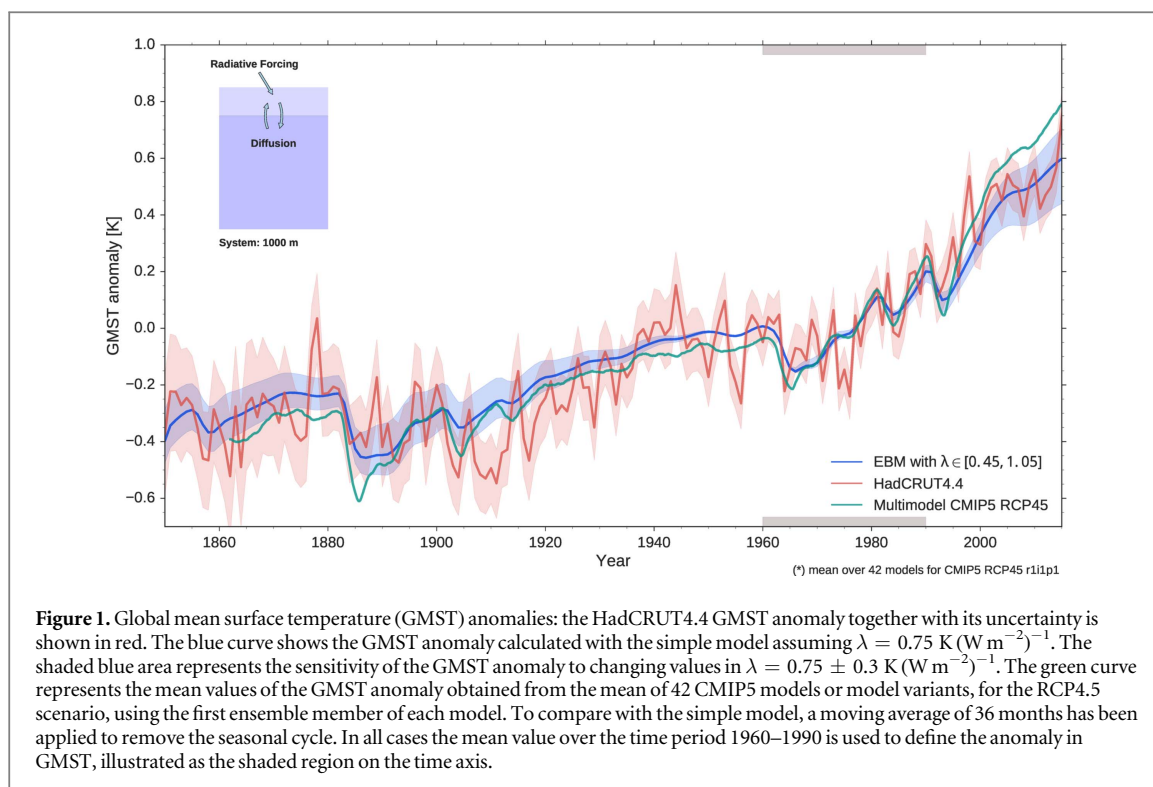
2. Data and methods

2.1. Simple climate model
We use a simple global-mean energy balance model (Hansen *et al* 1981, Shine and Highwood 2002) which consists of two boxes, one representing the atmosphere and ocean mixed layer (with assumed depth 100 m), and the other representing the deep ocean (with assumed depth 900 m) (see inset in figure 1). The changes in mixed layer temperature are taken to be the anomaly in GMST. The mixed layer is subject to a number of radiative forcing RF$_i$ the sum over which yields the total radiative forcing RF = ΣRF$_i$. The mixed layer and the deep ocean exchange energy via diffusion, assumed to be proportional to the difference between the GMST and the deep ocean temperature. Supplementary Data section S4 and table S4 provides more information on the model parameters used here. The climate system response is characterised by a climate sensitivity parameter λ and we explore the sensitivity of our results to the assumed value of λ over the range 0.3–1.05 K (W m^{-2})$^{-1}$. The performance of such a simple model in simulating historical temperature trends is discussed in section 3.1. We use the HadCRUT4.4 GMST dataset (Morice *et al* 2012 and www.metoffice.gov.uk/hadobs/hadcrut4/) for comparison and analysis.

2.2. RF datasets
The first step is to demonstrate that the simple model produces reasonable results, compared to Earth system models. For this purpose, we use all forcings (including the natural components) from the RCP4.5 scenario of Meinshausen *et al* (2011), which will approximate the historical RFs in the CMIP5 models.

To then isolate the roles of individual GHG components, we produce an updated series of RF for the period 1850–2014. The CO$_2$ RFs are from table AII1.2 of IPCC (2013a); because IPCC (2013a) does not provide separate RFs for other WMGHGs, we instead use Meinshausen *et al* (2011) for the period up to 2003, and then use the global-mean data from the Advanced Global Atmospheric Gases Experiment (AGAGE) (Prinn *et al* 2000) available at http://agage.eas.gatech.edu/data_archive/global_mean/. This includes time series of methane, nitrous oxide, 16 ODSs and 9 other fluorinated GHGs. We update the CO$_2$ RF to 2014 using global-mean concentrations from the NOAA data (http://esrl.noaa.gov/gmd/ccgg/trends/global.html). The RF for CO$_2$, methane and nitrous oxide is calculated from the concentrations and the standard expressions given in table 6.2 of Ramaswamy *et al* (2001). For all other WMGHGs, the radiative efficiencies are taken from table 8.A.1 of Myhre *et al* (2013). For tropospheric and stratospheric ozone and

Figure 1. Global mean surface temperature (GMST) anomalies: the HadCRUT4.4 GMST anomaly together with its uncertainty is shown in red. The blue curve shows the GMST anomaly calculated with the simple model assuming $\lambda = 0.75 \, \mathrm{K \, (W \, m^{-2})^{-1}}$. The shaded blue area represents the sensitivity of the GMST anomaly to changing values in $\lambda = 0.75 \pm 0.3 \, \mathrm{K \, (W \, m^{-2})^{-1}}$. The green curve represents the mean values of the GMST anomaly obtained from the mean of 42 CMIP5 models or model variants, for the RCP4.5 scenario, using the first ensemble member of each model. To compare with the simple model, a moving average of 36 months has been applied to remove the seasonal cycle. In all cases the mean value over the time period 1960–1990 is used to define the anomaly in GMST, illustrated as the shaded region on the time axis.

stratospheric water vapour due to methane oxidation, the values from table AII1.2 of IPCC (2013a) are used directly, and assumed constant between 2011 and 2014; this assumption has only a minor impact on the results presented here.

The supplementary data section S1 provides full information on the merged data set, including the list of gases included and the radiative efficiencies used for the fluorinated gases, as well as figures showing the time evolution. Supplementary Data section S2 provides results from an alternative data set derived from the NOAA Global Monitoring Division network (http://esrl.noaa.gov/gmd/) for comparison purposes. Supplementary Data section S3 presents the simple expressions used to derive the RFs.
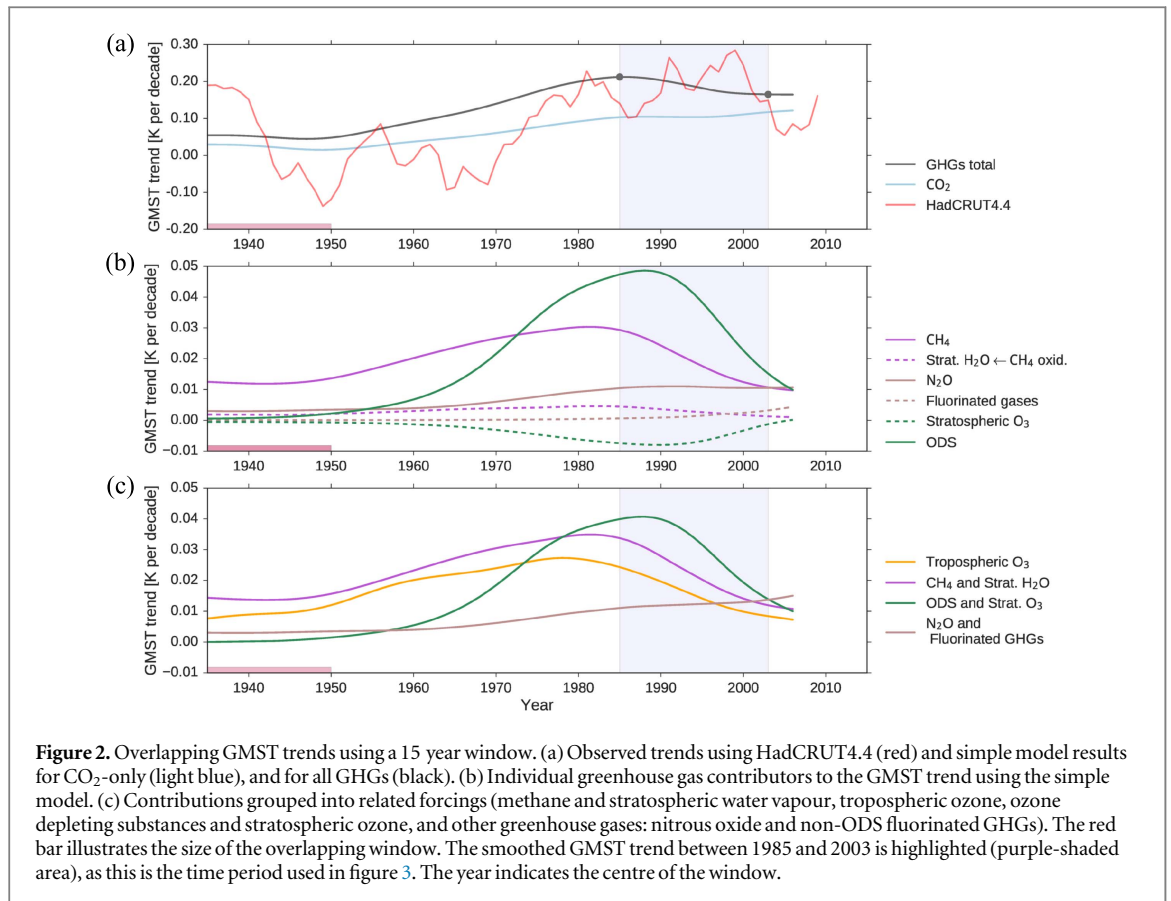
3. Results

3.1. Evaluation of simple model
We first compare results from our simple model with observations and more complex climate models (figure 1) to establish that it is a useful tool for the purposes here, prior to the assessment of the role of individual GHGs in section 3.2. For this, we include all (anthropogenic and natural) RFs from Meinshausen *et al* (2011). As well as comparing against the observed HadCRUT4.4 data, we also use results from CMIP5 integrations. We present the smoothed average from 42 CMIP5 models, or model variants, using the first ensemble member (r1i1p1) of each model's RCP4.5 simulation (IPCC 2013b) focusing on the historical period. Figure 1 shows that the simple model broadly reproduces the observed GMST anomaly given by

HadCRUT4.4 except for the high-frequency variability. The simple model reproduces both the hiatus between 1945 and 1960 and the slowdown around the year 2000. The simple model also broadly reproduces the results from CMIP5, although after 2000 CMIP5 systematically overestimates the GMST anomaly compared to HadCRUT4.4, as also shown in Fyfe *et al* (2016). The lower frequency oscillations of CMIP5 models between 1960 and 2000 are very similar to the simple model, indicating a similar response to the Pinatubo and El Chichón volcano eruptions. Finally, the uncertainty in the simple model due to the value of λ is similar to the 10%–90% range of the CMIP5 uncertainty shown by Fyfe *et al* (2016). These results demonstrate that the simple model is a useful tool for assessing the different greenhouse gas contributions to the recent slowdown.

3.2. The role of individual greenhouse gases in the rate of warming
Fyfe *et al* (2016) employed a method to demonstrate the slowdown based on overlapping trends of GMST anomaly with window sizes from 15 to 50 years. This method allows us to deal with the different timescales of the forcings, and at the same time avoid an arbitrary definition of when the slowdown begins and ends. Here we compute linear trends in both observed and simple-model GMST over a given window, with the value of that trend assigned to the middle of the window.

Figure 2 shows the GMST decadal trends for the GHGs contributions for a 15 year window size from the simple model, for a mid-range climate sensitivity

Figure 2. Overlapping GMST trends using a 15 year window. (a) Observed trends using HadCRUT4.4 (red) and simple model results for CO_2-only (light blue), and for all GHGs (black). (b) Individual greenhouse gas contributors to the GMST trend using the simple model. (c) Contributions grouped into related forcings (methane and stratospheric water vapour, tropospheric ozone, ozone depleting substances and stratospheric ozone, and other greenhouse gases: nitrous oxide and non-ODS fluorinated GHGs). The red bar illustrates the size of the overlapping window. The smoothed GMST trend between 1985 and 2003 is highlighted (purple-shaded area), as this is the time period used in figure 3. The year indicates the centre of the window.

parameter $0.75 \, \text{K} \, (\text{W m}^{-2})^{-1}$. The observed trend is shown for reference. The largest contributor to the total GHG-forced temperature trend (figure 2(a)) is CO_2, with values exceeding $0.1 \, \text{K decade}^{-1}$ in the early 1980s; in the 1985–2003 period (shaded box on figure 2(a)) it contributes to a steady or slightly increasing GMST trend. Despite this, figure 2(a) shows that, as a whole, the GHGs cause a reduction in warming trend, from 0.21 to $0.17 \, \text{K decade}^{-1}$, over this same period. The simulated reduction in trend was found to be relatively insensitive to the choice of λ, with the decrease ranging from 0.03 to $0.05 \, \text{K decade}^{-1}$.

Figure 2(b) shows the individual contributors to GMST trends for groups of non-CO_2 GHG forcings (methane, ODSs, nitrous oxide, and non-ozone-depleting fluorinated gases (such as the hydro-fluorocarbons) and stratospheric ozone). ODSs contribute the highest GMST trends during the entire period, but even at their mid-1980s peak, the trend is about a factor of two lower than that due to CO_2 (figure 2(a)). Nevertheless, ODSs are the dominant contributor to the GHG-induced slowdown, varying from $0.05 \, \text{K decade}^{-1}$ in the late 1980s to $0.01 \, \text{K decade}^{-1}$ by 2005; this contribution is slightly offset by the reduction in the negative RF due to the associated slow-down and reversal in stratospheric ozone trends. Although somewhat smaller, the methane contribution to the slowdown is still marked and is accentuated slightly by the related weakening of the growth

rate in stratospheric water vapour from methane oxidation.

Figure 2(c) groups together the ODSs and stratospheric ozone, methane and the associated stratospheric water vapour changes, and also shows the effect of tropospheric ozone. The ODSs plus stratospheric ozone depletion cause a reduction in the smoothed GMST trend between 1985 and 2003 by about $0.026 \, \text{K decade}^{-1}$, methane and stratospheric water vapour cause a reduction of $0.022 \, \text{K decade}^{-1}$, while tropospheric ozone causes a reduction of about $0.016 \, \text{K decade}^{-1}$; the sum of these (about $0.07 \, \text{K decade}^{-1}$) is a substantial fraction of the mean observed trend (about $0.2 \, \text{K decade}^{-1}$) over this period. It is off-set by the increasing trend due to CO_2, nitrous oxide and other fluorinated gases, but the total GHG effect is still a reduction in the trend by about $0.04 \, \text{K decade}^{-1}$. Our results hence do not support the conclusion of Pretis and Allen (2013) that the methane effect is small; the slowdown in methane growth rates are a significant contributor to the GHG-induced slowdown in GMST, and are only slightly smaller than the influence of the ODSs, when the offsetting effect of stratospheric ozone depletion is accounted for. Supplementary Data table S2 shows the values of the smoothed GMST trend for each component for the range of climate sensitivities used here.

In order to illustrate the dependence of the analysis on the choice of overlapping window size and λ, we employ a simple metric of the slowdown. This is

defined as the change in GMST trend (2003 minus 1985), divided by the observed-mean GMST trend averaged over the same period. Hence, a positive value indicates a higher GMST trend in 2003 than 1985, and a negative value a lower GMST trend; the size gives a sense of the importance of the change relative to the total observed GMST trend. We are not attempting to attribute the observed trend (or change in trends) to particular forcings; there are many forced and unforced contributors to the observed trend, as well as uncertainty in the simple model parameters, particularly climate sensitivity. The metric is intended to illustrate the importance of different drivers of GMST trends, and to explore the dependence of these drivers to changing values in the climate sensitivity parameter, as well as in the 'window' that is used in the smoothing.

Figure 3 shows the effect for different GHG drivers, and their total, for window sizes between 5 and 20 years and λ between 0.3 and 1.4 K (W m^{-2})$^{-1}$. It shows a weak dependence on window size, and the expected monotonic dependence on climate sensitivity. Because the Montreal Protocol caused a relatively abrupt change in the time variation of the ODS forcing, figure 3 shows that it is most sensitive to the choice of window size.

The changes in the constituent trends of the three groupings (methane plus stratospheric water vapour, ODSs plus stratospheric ozone, and tropospheric ozone) which contribute to the slowdown in GMST trends (figures 3(c)–(e)) can each cause slowdowns that reach or exceed 10% of the observed trend. CO$_2$ (figure 3(a)) causes an increasing trend, which is again about 5%–10%, and roughly equal but opposite to the effect of tropospheric ozone, while N$_2$O and the other fluorinated gases (figure 3(b)) cause a change which is only about 1%–2% of the observed trend. Figure 3(f) shows that for all window sizes and values of λ explored here, the GHGs together decrease the observed GMST trend in this period by between about 18% and 25%.
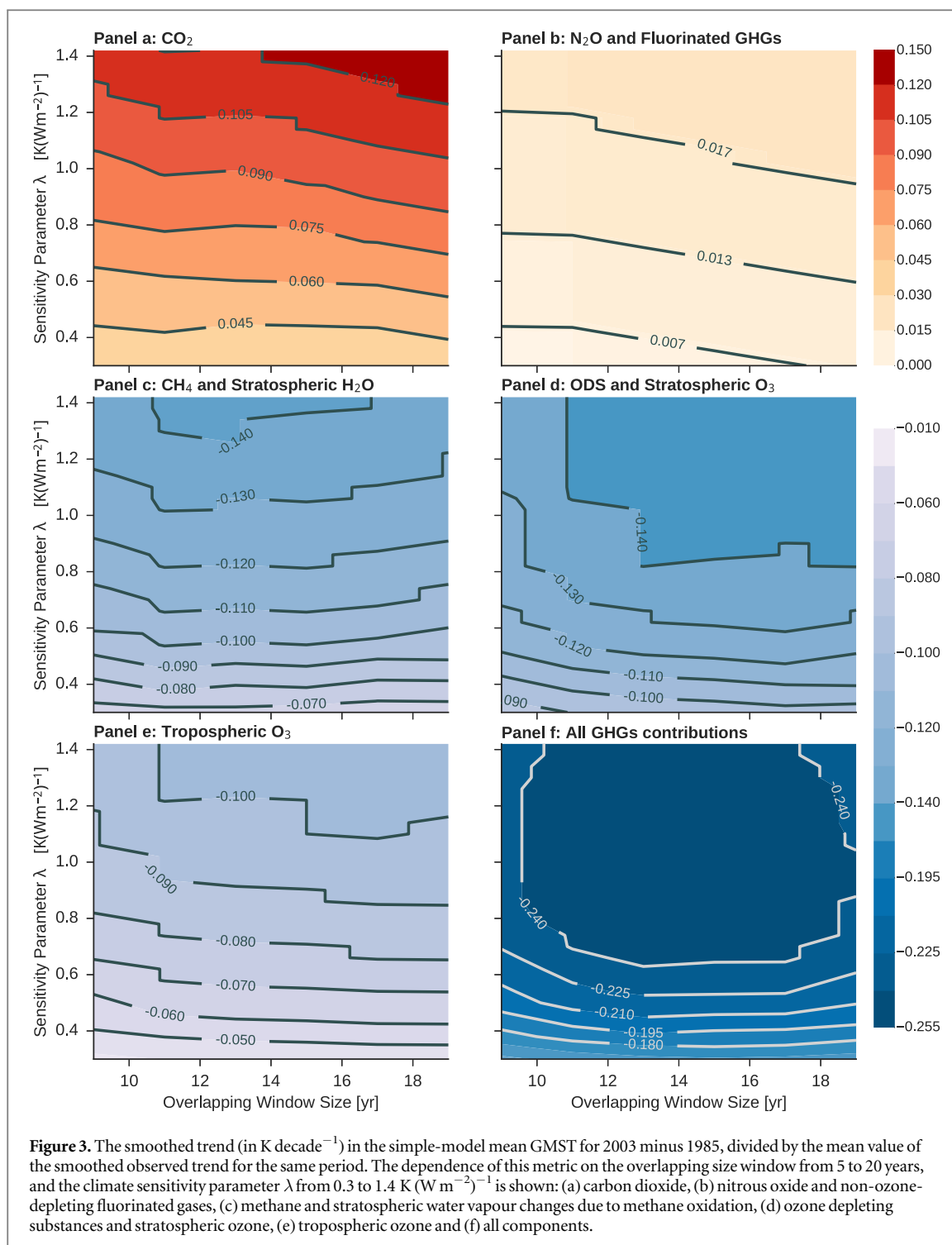
4. Discussion and conclusions

Our simple model results indicate that changes in the growth rate of greenhouse gases over the past two decades have exerted a significant impact on trends in GMST, reducing that trend by about 0.03–0.05 K decade^{-1}. Over the period 1985–2003, greenhouse gases drove a reduction of trend in GMST which was about 18%–25% of the observed trend itself (the stated ranges are for the range of climate sensitivities used here). Our study is the first to isolate the individual drivers of this trend. As expected, the reduction in emissions of ODSs is a significant component, although this reduction is slightly offset by the associated impact of the recovery of stratospheric ozone depletion on RF; the net reduction is 10%–15%

of the total observed trend. The slowdown in methane growth rates (and the associated impact on stratospheric water vapour) causes only a slightly smaller effect, with a reduction of 7%–14% of the total observed trend, and the slowdown in growth of tropospheric ozone also causes a reduction of 5%–11%. These three negative contributions are offset by an increase in GMST trend (4%–12%) due to CO$_2$, and a much smaller contribution from nitrous oxide and the non-ODS fluorinated gases.

Uncertainties in parameters other than climate sensitivity will also contribute to overall uncertainties, including simplifications in the simple model and in the simple expressions used to derive RF. In addition, it is assumed here that the climate sensitivity is the same for each component of forcing (which can be viewed as an assumption that the RF and the effective RF are the same). While the trends in the WMGHGs are well-characterized, trends in stratospheric and tropospheric ozone are much less well observed. Uncertainties in RF resulting from these changes are largest for the ozone components, In the present context, they are most important for tropospheric ozone, with Myhre *et al* (2013) giving a 90% confidence range of 0.2–0.6 W m^{-2} for the present-day forcing; uncertainties in the time evolution of that forcing may be as important here, and are much more difficult to characterize based on available observations. Myhre *et al* (2013) note that these uncertainties are likely much larger than the differences between RF and effective RF which accounts for fast adjustments.

Little previous attention has been given to variations in GHG concentrations in the context of the recent slowdown in GMST trends. Our results demonstrate that these variations can play a significant role. They emphasize the need for continued monitoring of greenhouse gas concentrations in the context not only of the overall change in climate, but in the time variations of that change. Nevertheless, the strongest impact of ODSs to GMST trends has already happened (following the transition from rapid growth in the late 1980s to peak concentrations around 2000); the expected slow decline of ODSs throughout the rest of this century will have only a modest impact on trends in GMST. Further, the renewed growth in methane concentrations since about 2007 (e.g. Nisbet *et al* 2014) is now acting to accentuate, rather than oppose, the dominant role of CO$_2$ in driving GMST trends due to GHGs. In supplementary data figure S2 we show the equivalent of figure 2, but using a shorter (5 year) window, which illustrates that after the year 2000, methane no longer contributes to a reduction of the GMST trend. Hence, unless there is an unexpected rapid decline in tropospheric ozone RF, or a reversal of recent upward methane trends, it can be expected that, as a whole, the GHGs will cause an acceleration in GMST trends in the near future.

Figure 3. The smoothed trend (in K decade^{-1}) in the simple-model mean GMST for 2003 minus 1985, divided by the mean value of the smoothed observed trend for the same period. The dependence of this metric on the overlapping size window from 5 to 20 years, and the climate sensitivity parameter λ from 0.3 to 1.4 K (W m^{-2})$^{-1}$ is shown: (a) carbon dioxide, (b) nitrous oxide and non-ozone-depleting fluorinated gases, (c) methane and stratospheric water vapour changes due to methane oxidation, (d) ozone depleting substances and stratospheric ozone, (e) tropospheric ozone and (f) all components.

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