RESPONSE TO THE INTERACTIVE COMMENTS
DURING THE DISCUSSION PHASE

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Rapid and reliable assessment of methane impacts on climate

Ilissa B. Ocko, Vaishali Naik, and David Paynter

We sincerely appreciate the careful reviews and helpful suggestions provided by the Reviewers, and thank the Reviewers and the Editor for their time. We have made several changes to the manuscript in response to the comments that have considerably enhanced the manuscript. Below, we have provided information on the major modifications to the text and responded point-by-point to comments (reviewer comments in blue, responses in black).

Major changes to the paper include:

- analysis and discussion of unforced variability in AM3/CM3 expanded and moved to the beginning of the results section rather than the end;
- an additional control run simulation performed to isolate unforced variability in AM3, and the results added to the figure with the CM3 control run results;
- more emphasis on unforced variability as an additional reason why simplified models are preferred tools for impacts of small changes;
- text modifications to caveat the difficulty in comparing simple model results with that from more complex models;
- inclusion of strategies to overcome the challenge of unforced variability;
- additional simulations performed using AM3 and CM3 to provide a different method for calculating the indirect (via chemistry) forcing and response due to historical methane changes;
- inclusion of reduced-complexity climate model options as alternatives to MAGICC;
- text modifications to reduce the impression that CM3 is “truth;” and
- addition of 14 new references.

Responses to RC1 (Anonymous Referee #1):

Comment 1: Too much of the paper is written in language that implies that the CM (or AM3) is validating MAGICC. While this is a natural assumption for large forcing (or large ensemble) cases, I am not sure this is necessarily the case here. The issue is that the overall transient response to historical methane forcing is around 0.5 deg C and the unforced variability in CM3 (Figure 7 and line 10-15) shows persistent and rapid unforced changes of this magnitude are possible. From a structural point of view, I feel that Figure 7 should be one of the first figures in the paper, rather than the last, where it appears as almost an afterthought. It should be accompanied by clear statement that there is a major difficulty in using ESMs to validate simple models in cases where the forcing is much less than, say, 1 W/sq.m, especially in ESMs where interannual variability is high. While the text in the intro and conclusions says that one issue is that CCMs are generally inaccessible, it could also be argued on the basis of this paper that they are potentially inappropriate tools when discussing small forcing scenarios. The issue is raised briefly at line 2-20 but the text never really returns to it when CM3 results are discussed.

Response: We thank the referee for the constructive feedback, and have made a number of changes in response to the comments.

We have reorganized the paper based on the referee's suggestion to include Fig. 7 as one of the first figures, and have considerably expanded analysis and discussion of unforced variability early in the paper and throughout the text. We have also run an additional simulation to assess AM3 unforced variability in addition to CM3, and added the results to the previous Fig. 7.

The reason that the paper was written as the CCM (AM3/CM3) validating MAGICC is because the CCM has a much more sophisticated treatment of relevant chemistry and physics, and therefore could be argued as more advanced in modeling climate responses to methane forcings—especially because it can resolve responses on regional scales and account for the spatially heterogenous response from chemical changes. However, because of the unforced variability in CCMs, we agree that an additional reason to use MAGICC is that it does not include unforced variability and therefore can more clearly address changes in small forcing scenarios, and have expanded the discussions in the text to reflect this—including acknowledgement in the abstract as both a motivator and result of our study. We have also toned down the language that implies that CM3 is "truth" in this analysis.

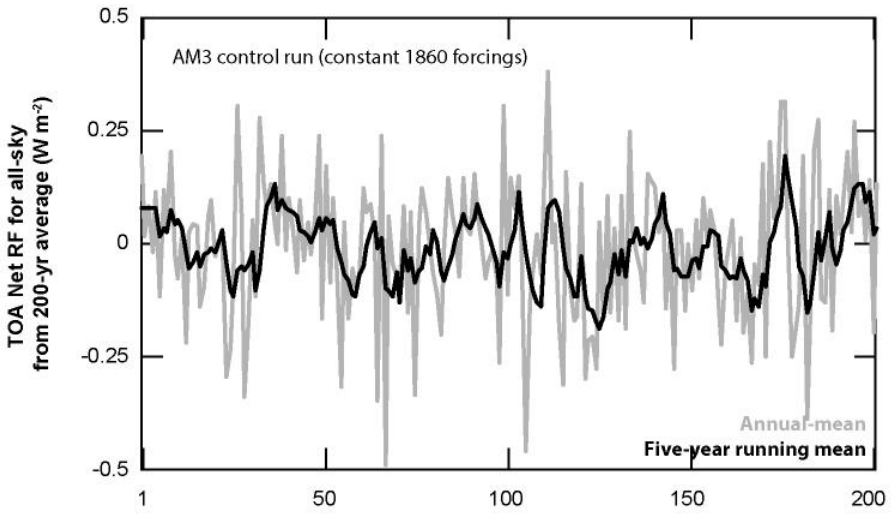
Comment 2: I have a related concern about the (unforced) radiation budget variability in AM3, and how this looks compared to available observations. I note "unforced variability" in AM3 is briefly mentioned at 7-28 and 8-11, but it is unclear whether this is a major or minor issue. This is important to know for understanding the reliability of forcings derived from AM3 simulations (in Figure 2 and 3) - there are several surprising

features in those forcings which may have their origin in this variability. These include the fact (line 8-9) of the AM3 methane forcing being close to that of CO2 before 2000, and exceeded it in the 1970s (which, if substantiated, would constitute a major result) and the fact that (line 8-12) AM3 methane forcing decreases when methane is flat (how can that be?) and others referred to below. I am a bit suspicious as to how and why the AM3 methane and CO2 forcings diverge after 1995 after being so close to each other before this and would like to see a clearer explanation on page 8. See also my main comment on 7-25.

Response: We thank the reviewer for the thoughtful comments. In order to evaluate the unforced variability in AM3, we have run AM3 with 1860 forcings for 200 years with a repeating seasonal cycle of sea surface temperatures and sea ice for each year (see figure below of a time series of net radiation at the top-of-atmosphere for all-sky conditions for annual and 5-year running mean averages, which has also been added to the new Figure 2 in the paper). We find that based on unforced variability, one year averages can easily have swings of 0.8 Wm-2, while 5-year averages is around 0.35 Wm-2. Ten-year averages is better at ~0.20 Wm-2.

Comparing this run to the CO2-only and methane-only AM3 forcings (5-yr averages) and using the MAGICC forcings as a baseline, we find that all of the deviations of CO2-only AM3 forcings, and nearly all of the deviations of methane-only AM3 forcings, fall within 0.35 W/m2 from the baseline. Therefore, it is very likely that the unforced variability in CM3 is the source of these variations, and this is another reason why a reduced-complexity model unfettered by unforced variability is useful. We have clarified both of these points in the text (lines 10-12 – 10-15): "*Some unexpected features in AM3 forcings (such as negative forcings in the earlier years despite increasing atmospheric concentrations) are likely due to unforced variability. Using the MAGICC forcings as a benchmark for a signal due to forced changes only, we find that nearly all of the deviations of AM3 fall within the range of internal variability as derived from the control simulation: 0.35 W m-2.*"

However, we note that the AM3 methane and CO2 forcings diverging after 1995 is consistent with the leveling off of atmospheric methane concentrations around the mid-90s and through the mid-2000s (see Figure 1 in the paper) and this is acknowledge in the paper.



Comment 3: The lack of clarity about the large unforced variability in CM3 until near the end means that some of the earlier discussion attempts a too deterministic analysis of CM3-MAGICC differences.

Response: We appreciate this observation, and have reorganized the discussion to address unforced variability in AM3 and CM3 in the beginning of the Results section, considerably expanding the text and analysis, and have referred back to this variability throughout the rest of the text.

An example of the reframed discussion include (lines 9-20 – 10-5): "*Given that an important difference between AM3/CM3 and MAGICC results is the role of unforced variability in AM3/CM3, we first analyse the magnitudes of unforced variability in both AM3 and CM3. Although initial condition-driven ensemble member means and/or running averages are employed to dampen out some of the variability in AM3/CM3, it still plays a large role in forcing and temperature responses. CM3, in particular, has been shown to produce magnitudes of variability on the upper end of CMIP5 models (Brown et al., 2015).*

The results of the control simulations with constant preindustrial (1860) external radiative forcings are shown in Fig. 2. In the case of AM3 unforced radiative forcings at the top-of-atmosphere for all-sky conditions range from -0.18 to 0.21 W m-2 with a standard deviation of 0.07 W m-2 for a five-year running mean. We find the maximum swing between two consecutive five-year means to be 0.35 W m-2. Sources of unforced variability in AM3 include a mixture of land snow/ice cover variability and just year-to-year variability in the weather; soil moisture may also play a role. For CM3, unforced internal dynamics yield temperature responses ranging from -0.27 to 0.24 °C for five-year running means with a standard deviation of 0.1 °C. We find the maximum swing between two consecutive five-year means to be 0.2 °C. The variability is driven by interactions among the ocean-atmosphere-land systems. While unforced variability is a key component to modelling the climate system, it can mask or amplify responses to

external forcings over short timescales (e.g., Brown et al., 2017). This makes it difficult to clearly assess responses to small external forcings, and provides further motivation for using simpler models like MAGICC for analysis of small forcing scenarios."

Comment 4: Specific comments:

4-26: The paper uses two quite different meanings of ensemble but does so in an interchangeable way. At 4-19, the MAGICC ensemble could be considered a perturbed physics one. At 6-24 the CM3 ensembles are initial condition ensembles. This major distinction gets lost later, for example, in Fig 5 caption, but I have other concerns. Is a 3-member ensemble CM3 considered enough given the size of the applied forcing (and the size of this model's unforced variability)?

Response: The needed clarity for ensemble definition differences is a great point by the referee. We have clarified the differences in the definitions for CM3 and MAGICC using qualifiers throughout the text and figure captions as: "initial condition-driven ensemble members" for CM3 and "physics-driven ensemble members" for MAGICC.

The 3-member ensemble collection for CM3 is a standard practice for models of this scale due to limitations of computational resources. While small, studies have shown that forced changes in air temperature (as opposed to changes in atmospheric circulation and precipitation) can be detected with fewer ensemble members (Deser et al., 2010). We have now included this caveat in the text (lines 8-8 – 8-10: "*While three ensemble members is relatively small, we are limited by computational resources and studies have shown that forced changes in air temperature, as opposed to changes in atmospheric circulation and precipitation, can be detected with fewer ensemble members (Deser et al., 2012).*"

Deser, C., Phillips, A., Bourdette, V. and Teng, H., 2012. Uncertainty in climate change projections: the role of internal variability. Climate dynamics, 38(3-4), pp.527-546.

While I appreciate the point made at 6-19 to 6-22, would it be useful to highlight the MAGICC configuration that matches CM3 as closely as possible, particularly for climate sensitivity? As far as I can tell (and sorry if I miss it) the reader is never told what the climate sensitivity of CM3 is, and therefore it is hard to judge whether it might be an outlier in the MAGICC ensemble.

Response: As noted in the text and appreciated by the referee, the reason that we do not tune the properties of MAGICC to match that of CM3 is because we are trying to determine if MAGICC as it currently exists and is used can effectively reproduce climate changes in response to methane emissions. While tuning MAGICC to be more like CM3 would yield responses more similar to CM3, this is not how MAGICC is and will be used in the future. Here we show that based on

MAGICC's current properties it is sufficient in modeling climate responses to changes in methane emissions.

However, we appreciate the feedback of the referee in inquiring about the MAGICC configuration that matches CM3 the most. We have therefore provided information on CM3's climate sensitivity (4.8 K based on multimillenial simulations (Paynter et al., 2018)) as well as noted that two of MAGICC's physics-driven ensemble members are derived from two predecessors of CM3: CM2.0 and CM2.1.

Paynter, D., Frölicher, T.L., Horowitz, L.W. and Silvers, L.G., 2018. Equilibrium climate sensitivity obtained from multimillennial runs of two GFDL climate models. Journal of Geophysical Research: Atmospheres, 123(4), pp.1921-1941.

Finally, I presume the AM3 results were not from an ensemble?

Response: The referee is correct in that the AM3 results were not from an initial condition-driven ensemble, because they were driven by observed SST and SIC. We have clarified this in the text (lines 8-13 – 8-15): "*The model configuration of AM3 was exactly the same as CM3 except AM3 model integrations over the period 1870 to 2014 were performed with observed sea-surface temperature and sea-ice cover (Rayner et al., 2003), and therefore do not include an ensemble driven by different initial conditions*."

7-25 and Figure 2: I understand that stratospheric aerosol RF is not a topic for this paper, but the difference between MAGICC and AM3 is very striking and it seems that the AM3 forcing from individual volcanoes is persisting for unrealistic lengths of times (most notably Agung) and leaves a signature which looks unrealistic in the surface temperatures (in Figure 4). Has this been discussed in earlier papers? Is it some lingering indirect effect of the eruptions? Is it due to the smoothing process? I feel it should be mentioned briefly here, not least because it may impact on the ability to extract the methane signal from CM3.

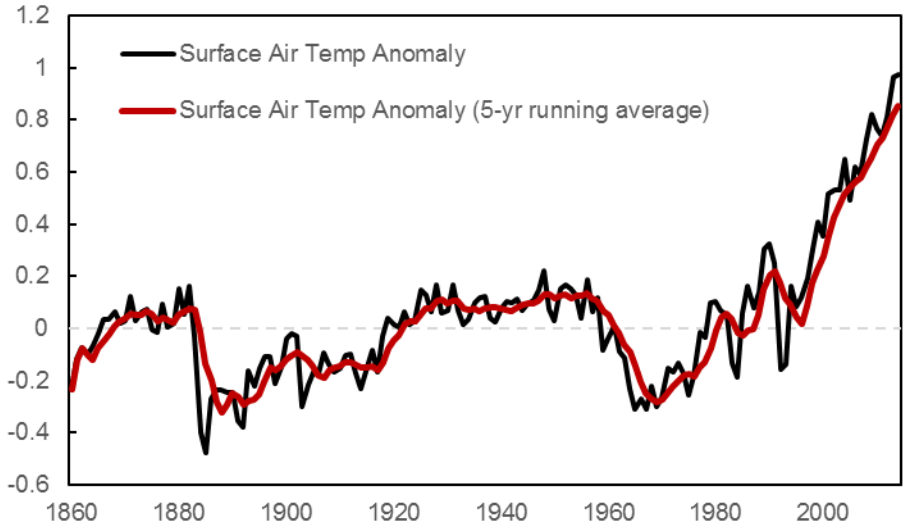
Response: We thank the reviewer for this observation. Upon further investigation, it appears that the "lingering" volcanic signature is mainly due to the 5-year running mean smoothing process (see figure below). We have added this caveat to the text (lines 11-31 – 12-3): "*We note, however, that the 'lingering' temperature response in CM3 to major volcanic eruptions is an artefact of the 5-year running mean smoothing process; this is why CM3 temperature responses to volcanic eruptions persist longer than what is seen in the observational records and by MAGICC. This is not found, however, to considerably impact the correlation coefficients between the CM3 data and the NOAA/NASA data.*"

CM3 simulates the impact of 'explosive' volcanic aerosols via an imposed time series of volcanic optical properties (from Stenchikov et al. (2006)) rather than direct injection of sulfur into the stratosphere (Donner et al., 2011). We have

clarified this in the text (lines 6-25 – 6-27): "*'Explosive' volcanic eruptions are imposed via a time series of volcanic optical properties rather than from direct injection of sulfur into the stratosphere (Stenchikov et al., 2006; Donner et al., 2011).*"

The response of surface temperature to volcanic forcing from CM3 is discussed in several previous papers (Austin et al., 2013; Golaz et al., 2014; Merlis et al., 2014), and what we show in our paper is similar to that shown by Golaz et al. (2014) Figure 3 (attached below), which also employs a 5-year running mean.

CM3 all-forcing temperature anomalies:



Golaz et al. 2013, Fig. 3:

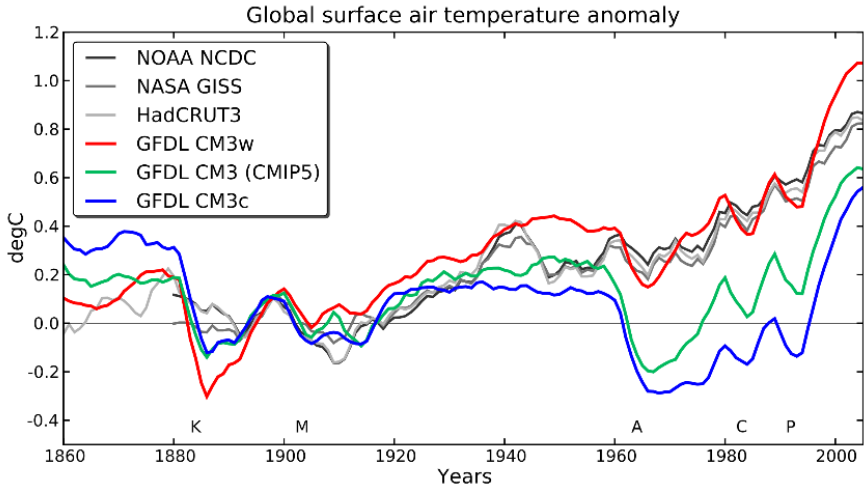


Figure 3. Time evolution of global mean surface air temperature anomalies. Color lines represent the CMIP5 GFDL CM3 model (green) and the two alternate configurations, CM3w (red) and CM3c (blue). Each line is a five-member ensemble average. Anomalies are computed with respect to 1881–1920. Model drift is removed by subtracting from each ensemble member the linear trend of the corresponding period in the control simulation. Also shown are observations from NOAA NCDC [*Vose et al.*, 2012], NASA GISS [*Hansen et al.*, 2010], and HadCRUT3 [*Brohan et al.*, 2006]. A 5 year running mean is applied to model results and observations. Letters above the horizontal axis mark major volcanic eruptions: Krakatoa (K), Santa María (M), Agung (A), El Chichón (C), and Pinatubo (P).

Austin, J., Horowitz, L.W., Schwarzkopf, M.D., Wilson, R.J. and Levy, H., 2013. Stratospheric ozone and temperature simulated from the preindustrial era to the present day. Journal of Climate, 26(11), pp.3528-3543.

Donner, L. J., Wyman, B. L., Hemler, R. S., Horowitz, L. W., Ming, Y., Zhao, M., Golaz, J. C., Ginoux, P., Lin, S. J., Schwarzkopf, M. D. and Austin, J.: The dynamical core, physical parameterizations, and basic simulation characteristics of the atmospheric component AM3 of the GFDL global coupled model CM3, J. Clim., 24(13), 3484–3519, 2011.

Golaz, J.C., Horowitz, L.W. and Levy, H., 2013. Cloud tuning in a coupled climate model: Impact on 20th century warming. Geophysical Research Letters, 40(10), pp.2246-2251.

Merlis, T.M., Held, I.M., Stenchikov, G.L., Zeng, F. and Horowitz, L.W., 2014. Constraining transient climate sensitivity using coupled climate model simulations of volcanic eruptions. Journal of Climate, 27(20), pp.7781-7795.

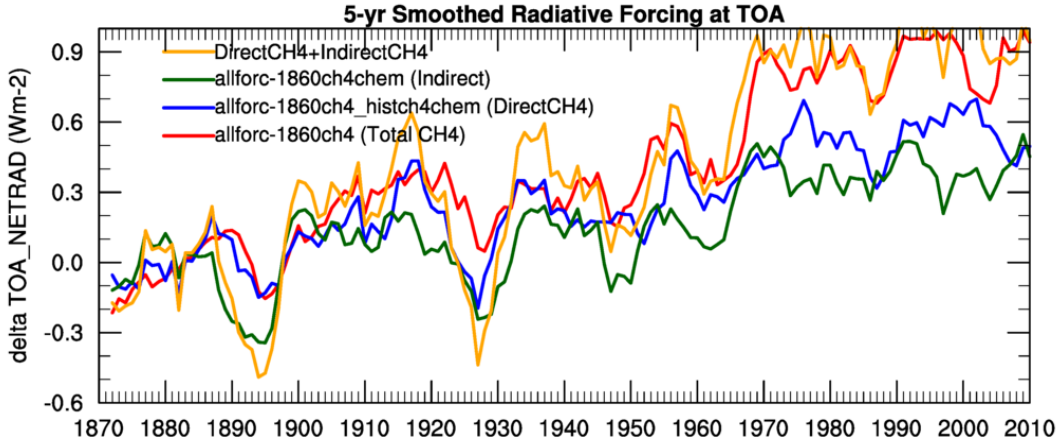
Stenchikov, G., K. Hamilton, R. J. Stouffer, A. Robock, V. Ramaswamy, B. Santer, and H.-F. Graf, 2006: Arctic Oscillation response to volcanic eruptions in the IPCC AR4 climate models. J. Geophys. Res., 111, D07107, doi:10.1029/2005JD006286

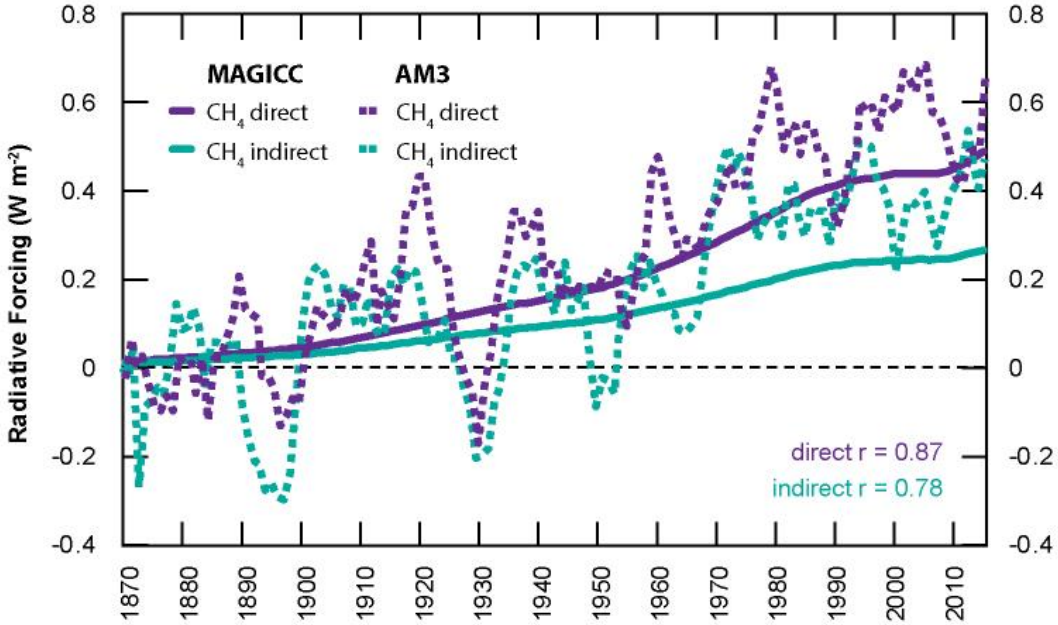
8-14 and Figure 3: There are quite a few concerning features in this figure, which leads on from my other comments. Given the smoothly varying methane concentration (Figure 1) how can the direct AM3 forcing fluctuate so rapidly? Is this just the unforced variability of the radiation budget in AM3? Also it seems that there is a strong degree of anticorrelation between the AM3 direct and indirect forcings most apparent in some periods (1920-1940 and 1980 onwards) which lead to the total forcing (in Figure 2) being much smoother – so again, is this anticorrelation just an artefact of the analysis method, or robust? Finally, the fact that the methane indirect forcing falls to near zero in the 2000's would, if correct, constitute a major result. The text (8-20) says that it is "mostly tropospheric ozone" but this needs substantiating by showing some measure of the tropospheric ozone variations in AM3, and some assurance that the feature is a clear signal above the noise.

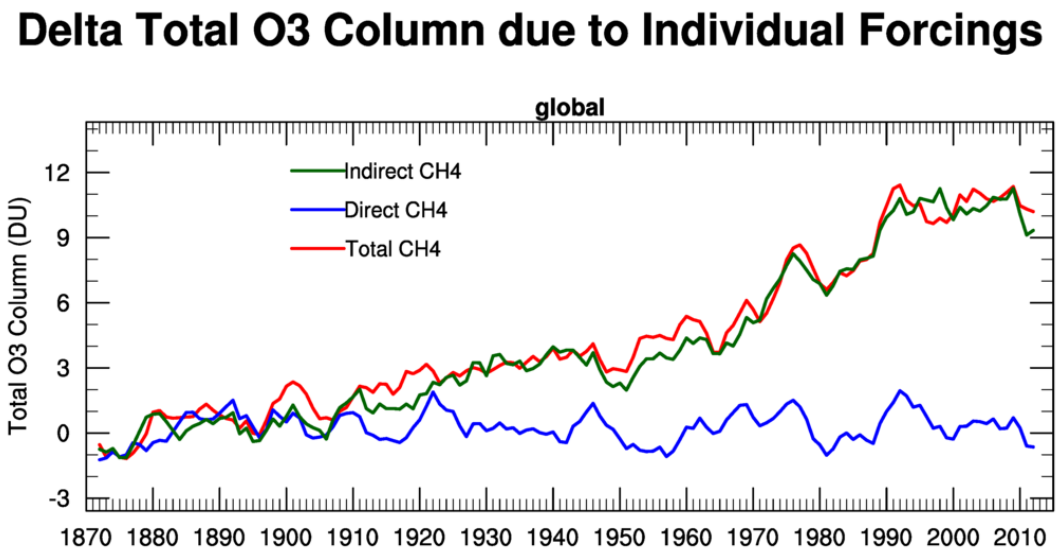
Response: Further investigation revealed that most of the anti-correlation and many of the 'peculiar' features was indeed an artefact of the analysis method. We ran additional simulations to calculate the indirect methane forcings and responses via modifications to chemistry rather than our original method that introduced a double subtraction to determine the indirect effects. We ran AM3 and all ensemble members of CM3 for an experiment where methane radiation varied with time but chemistry was held at 1860 methane levels. We found that this new methodology resolved many of the issues, including the majority of the anti-correlation features as well as the near-zero indirect forcing around the year 2000 (see new figure 4 in paper and below).

We have therefore updated the manuscript to reflect this new methodology for indirect effects of methane, keeping the original methodology for direct effects of methane. This method is also more consistent with how we calculated indirect effects of methane in MAGICC. While the direct and indirect effects are not completely additive (see figure below) this is typical nonlinearity effects for models of this complexity. To address the referee's comment about the ozone behavior for the different experimental setups, we plotted the below figure. This shows that total ozone column changes that we see are greater than zero due to CH4 at present-day.

Further, we note that unforced variability in AM3 does play a considerable role in the temporal evolution of forcings. We have run AM3 with 1860 forcings for 200 years with repeat sea surface temperatures and sea ice for each year (see new Figure 2). We find that based on unforced variability, one year averages can easily have swings of 0.8 Wm-2, while 5-year averages is around 0.35 Wm-2. Ten-year averages are better at ~0.20 Wm-2. Sources of unforced variability in AM3 include a mixture of land snow/ice cover variability and just year-to-year variability in the weather; soil moisture may also play a role. For indirect methane forcings in AM3, the anomalies from a MAGICC benchmark all fall within 0.25 Wm-2, which is within the realm of unforced variability. We have clarified this in the text (lines 9-25 – 9-29): "*In the case of AM3 unforced radiative forcings at the top-of-atmosphere for all-sky conditions range from -0.18 to 0.21 W m-2 with a standard deviation of 0.07 W m-2 for a five-year running mean. We find the maximum swing between two consecutive five-year means to be 0.35 W m-2. Sources of unforced variability in AM3 include a mixture of land snow/ice cover variability and just year-to-year variability in the weather; soil moisture may also play a role.*"







8-6 to 8-13: I have quite a few comments on this paragraph. (i) I think comparison of MAGICC with IPCC needs to be more carefully done. I am almost certain they both use the same radiative forcing expressions and hence the only reasons for differences would come from different scenarios of trace gas change, and possibly different handling of N2O overlap. (ii) wording like “MAGICC reasonably reproduces : : : AM3” (8-6) and “not captured by MAGICC” (8-11) implies to me that there is a belief that the AM3 radiation code is superior to the radiative transfer codes used to generate the RF

expressions in MAGICC and IPCC. Of course, this may be the case, but if this cannot be established with certainty, the wording should be more cautious. And as noted in my general comment (2) without knowing the size of the unforced variability in AM3 it is hard to place any differences in perspective.

Response: We appreciate the thoughtfulness of this comment and agree with the referee on several of their points. While the same radiation parameterizations are used for IPCC and MAGICC for carbon dioxide and methane atmospheric concentrations, we believe that it is the way that tropospheric ozone in MAGICC (and other short-lived trace gas chemistry) is simulated that is causing a difference between IPCC and MAGICC methane RFs. While minor differences exist in the definition of baseline (IPCC RFs are calculated with a 1750 forcing baseline, and MAGICC RFs is calculated with a 1765 forcing baseline but we adjust to 1860 to compare with CM3); and present-day concentrations (at 2011, CO_2 concentrations in IPCC and MAGICC are391 ppm and 393 ppm, respectively; CH4 concentrations in IPCC and MAGICC are 1803 ppb and 1782 ppb, respectively), the simplified treatment of tropospheric ozone forcing in MAGICC due to virtually no spatial resolution because of hemispheric averages is very different than the vastly more sophisticated multi-model studies under Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) that are used in IPCC AR5. This is also one reason why we imply that the sophisticated models (such as AM3) are superior in radiation code to that by MAGICC.

We have greatly clarified and addressed all of this in the text (lines 10-24 – 11-3): "*Preindustrial to present-day forcings for CO_2 and methane simulated by AM3 and MAGICC are similar to those given by IPCC (Myhre et al., 2013), (1.68 from CO2 emissions and 0.97 W m-2 from methane emissions in 2011 relative to 1750 levels), albeit there are important differences, including baseline years (1750 for IPCC and 1870 for AM3 and MAGICC in this study to match that from AM3) and time series of atmospheric concentrations (Myhre et al., 2013). While the same radiation expressions are used for IPCC and MAGICC for CO2 and methane atmospheric concentrations, the representation of tropospheric ozone chemistry and its radiation effects in MAGICC is extremely simplified due to hemispheric averages in a four-box atmosphere. For a short-lived climate forcer that is highly spatially variable, this is a vastly different treatment than that by the IPCC, which employs multi-model assessments for tropospheric ozone forcings. We find that our direct methane forcing in MAGICC in model year 2011 is 0.45 W m-2, extremely close to the IPCC's forcing of 0.48 W m-2 from changes in methane concentrations alone (recall however different baselines) (Myhre et al., 2013). However, when methane interactions with other chemical species are accounted for, MAGICC estimates a forcing of 0.7 W m-2 attributed to changes in methane compared to the IPCC's value of 0.97 W m-2 (Myhre et al., 2013).*"

9-13: It is hard to know what conclusions to draw from this paragraph – is it that the

CM3 signals are unreliable because of the difficulty of extracting a small signal from a small ensemble given the size of the unforced variability (especially in the 1900-1915 period when methane forcing was less than 0.2 W m-2)?

> **Response:** The purpose of this paragraph was to address two prominent, but unusual, features of temperature responses to methane. We agree with the reviewer that this was confusing and could be made a lot clearer. We have therefore clarified the text to address the features but also explain their significance for our study (lines 12-15 – 12-26): "*Two major features of the temperature response to methane in CM3, that are not present in MAGICC, further highlight the difficulty of extracting a small signal (and with a small ensemble) given the size of the unforced variability (Fig. 6); methane's forcing is considerably smaller than that of CO2, making it difficult to extract a temperature response from the variability.. The first feature is a global mean cooling response to methane forcings around 1900 to 1915, which is strongly apparent in two of the three initial condition-driven ensemble members. This cooling response is not clearly reflected in the forcings of both the direct and indirect methane responses, and while total methane forcings in AM3 are slightly negative (at most -0.15 W m-2) from 1895 to 1900, they are positive (around 0.2 W m-2 on average) from 1900 to 1915 (Figs. 3 and 4). The second feature is a strong warming signal in response to methane from 1980 to 1995, followed by cooling through 2000; while this is consistent with AM3 RFs (Fig. 3), the feature is more pronounced in the temperature response. Both of these features fall within the range of annual temperature swings due to unforced variability in CM3 (at most around 0.2 ºC for a five-year running mean). Therefore, we cannot conclude that they are robust responses to methane, but rather serve as a further example of why CCMs are difficult to employ for small individual forcings and the need for large ensembles*."

10-10 and especially 10-13: Again it is hard to know what conclusion to draw here, and there is nothing to lead the reader. I believe that this paragraph should come much earlier in the paper and be flagged as a major caveat when trying to extract small signals from ESMs, and in particular CM3 given its such large variability. As it is, this aspect is presented almost as an afterthought.

> **Response:** We thank the referee for this suggestion, and we have moved this paragraph to the beginning of the results section, to better ground the rest of the discussion in the context of internal variability. Further, we have expanded the paragraph based on other feedback herein, and ran an additional simulation to analyze the role of unforced variability in AM3. We have also moved the last figure to the beginning of the paper, and expanded it to include AM3 as well. Throughout the text, the narrative has been modified to address

11-12: "useful threshold" – I agree with this, but I don't believe the paper applies this threshold. If it did, I think one conclusion could be that some of the early 20th century signals attributed to methane in AM3/CM3 are not robust and should not be interpreted as

such. This may be what 11-13 to 11-15 is trying to say. If so, it needs to be stated more clearly, earlier in the paper and reflected in the abstract.

> **Response:** We appreciate this feedback, and ultimately decided to remove and/or modify some of the text. It now read (lines 14-10 – 14-19): "*Further, we find that methane accounts for a considerable fraction of 20th Century and early 21st Century warming—roughly half that of CO2's warming response. However, there are some features present in CM3 results without parallels in MAGICC. The features are, however, consistent in magnitude with forcing and temperature fluctuations due to unforced variability, and therefore are unable to be classified as robust responses. A good example of this is that CM3 exhibits a cooling response to methane from 1900 to 1915 likely due to the formation of the southern ocean polynya leading to very large unforced multidecadal time-scale climate variability. This highlights how unforced variability present in sophisticated models can make it difficult to ascertain robust responses to small changes in multiple forcings individually, further justifying the use of a model such as MAGICC beyond pure accessibility. To overcome this challenge, a larger number of ensembles could be employed or simulations can be run with a quasi-chemistry-transport model (Deckert et al. 2011).*

Comment 4: Additional comments

Throughout: I suggest that the 4 in CH4 is subscripted throughout, for consistency with CO2.

> **Response:** We have made these changes.

Throughout: There is a lack of consistency in the labelling of simulations – compare the abbreviation column of Table 1 with Equations (1) to (4).

> **Response:** We have made the Table and Equations consistent in their labeling.

1-7: The abstract does not highlight any of the scientific results emerging from CM3 – the fact that methane-induced warming is competitive with CO2 for long periods and the high variability of its indirect effect. My other comments indicate some skepticism about these results, but it seems odd not to mention them at all in the abstract if the authors stand by them.

> **Response**: Further analysis of the unforced variability indicates that we cannot confidently say that any of these features are from the forced changes (they are all within the range of swings shown in the control runs (no external forcings)). Therefore, we have modified the text throughout the paper to make this clear, using the results (such as the fact that methane-induced warming is competitive with CO2 for long periods and the high variability of its indirect effect) as examples of why a reduced-complexity climate model is a better tool, and have

emphasized the importance of unforced variability in the abstract, especially as a justification for using MAGICC.

2-3: I suggest this sentence is re-worded to avoid the appearance of policy advocacy. The standard and effective IPCC wording is "if we want to avoid warming then we need to reduce emissions".

Response: We have made these changes.

2-10: I looked at Etminan's paper and could see nothing on temperature change.

Response: Etminan's paper substantiates the claim that methane emissions account for a quarter of today's positive radiative forcing (via radiative forcing of methane), and also provides the data for the calculation that today's anthropogenic methane emissions will have a larger impact on near-term warming than today's fossil fuel emissions (via GWP calculations based on new radiative efficiency of methane). However, we see how this was confusing and have tried to clarify what information was from each source in the text (lines X-X): "*Methane emissions in particular account for a quarter of the excess energy trapped by human emissions, and today's global anthropogenic methane emissions will have a larger impact on near-term warming than today's global fossil fuel CO2 emissions (based on forcing data provided in Myhre et al., 2013 and references therein; methane emissions provided in EPA, 2012; CO2 emissions provided in IEA, 2015; and radiative efficiency estimates of methane provided in Etminan et al., 2016).*"

2-16: For sure, the GWP concept has a lot of problems, but the strong variation of its value with time horizon (e.g. compare GWP(20) with GWP(100)) does capture "important temporal distinctions".

Response: This is true, however GWP is almost always employed with one time horizon selected by the user. We have clarified in the text that the way GWP is currently used (selection of a single time horizon) does not capture temporal distinctions *unless* two time horizons are employed simultaneously (e.g. Ocko et al., 2017).

4-1 and 4-7: Is it correct that MAGICC is driven by concentrations for 1765-2005 and emissions for 2006-2014? The fact that the methane lifetime is mentioned as being updated at 6-15 adds to confusion as to whether the model is concentration or emission driven. The (possible) emission/concentration confusion is also present in the paragraph after 6-15. But then 7-17 and Figure 1 seems to clearly imply that both models are concentration driven. So I ended up a bit confused.

Response: Yes, MAGICC is driven by concentrations up through 2005 and then emissions thereafter. We understand how that is confusing with lifetime properties being updated, and have clarified in the text, and also Figure 1.

4-15: There are significant differences in the CO2 expression used in the two references given here – I doubt that MAGICC uses the IPCC FAR expression.

> **Response**: MAGICC v6 uses the IPCC FAR expression (Shine et al., 1990) but with an updated scaling parameter from Myhre et al. (1998). Please see: http://wiki.magicc.org/index.php?title=Radiative_Forcing. We have clarified this in the text.

4-25: Units of climate sensitivity missing.

> **Response:** We have added the units.

5-19: A minor query, but I wasn't sure what the "indirect feedbacks of CH4 on CO2" were – it could include the fact that CH4 is oxidised to CO2, or that CH4-induced climate change impacts the carbon cycle or CH4-induced changes in O3 impact the carbon cycle by their effect on vegetation (or all three).

> **Response:** We meant that CM3 CO2 concentrations do not get altered by reactions that occur in the model, and have clarified this in the text.

6-15: Coupled with my comment at 4-15, I am confused. Does MAGICC use the AR5 forcing expressions for methane or does it use the radiative efficiencies (which are W m-2 ppbv-1 normally defined for small perturbations from present day)? I don't think MAGICC can use both and this needs to be clarified.

> **Response**: We agree with the referee that this is confusing, and we appreciate the careful attention to the details in our paper. The MAGICC v6 documentation (Meinshausen et al. 2011) specifies the forcing expressions when discussing radiative forcing routines for methane, and we ran additional MAGICC simulations to test the sensitivity of climate responses to changed methane radiative efficiency inputs, and they scaled proportionally. The radiative forcing expressions are used to handle the overlapping absorption bands between methane and nitrous oxide, and also take the radiative efficiency into account. We have clarified this in the text.

7-6: I found this sentence a bit cryptic. Presumably N2O and its overlap are considered in the AM3 radiation code? I was not sure why the dependence should lead to a "likely overestimate" of methane forcing.

> **Response**: The radiation code does indeed account for the spectral overlap, and we have removed the confusing sentences in the paper.

8-28: I don't agree with NASA and NOAA temperature series being labelled as "independent observational datasets" when there is, of course, a huge commonality in the

underlying data, and I believe in some of the applied corrections to that data. A better wording could be used.

Response: We have removed the word independent.

11-1: “accurately” – the word “adequately” is used at 9-1 and I believe it a much better description of Figure 4.

Response: We have made this change.

11-21: One issue with MAGICC is that (as I understand it) only the executable, rather than the source code, is available, which is at odds with the title at 11-19. It may be worth making this clear to readers.

Response: We have clarified this in the text.

18-4: Delete “technically”?

Response: We have made this change.

Responses to RC2 (Anonymous Referee #2):

Comment 1: Simplified models have beside the lower need of computational resources the advantage that the internal variability is small or zero and it is possible to assess the impact of small changes, while the internal variability in complex models is too large therefore. But this makes it at the same time difficult to compare them and evaluate the simplified model. As Reviewer #1 stated it is difficult to evaluate forcings which are in the same order as the unforced internal variability (Fig 7) and the variation of different ensemble members (e.g. Fig. 5, 1960). The fact that the internal variability of CM3 is very large compared to CMIP5 models, should be mentioned earlier in the text to make it easier to put the results in the right context. The text is partly formulated as CM3 is the truth and MAGICC should reproduce the same features. While this is important if the features are physically base, it is not the case if the features are due to internal variability, as the benefit of simplified models is that the results are almost free of internal variability. Additionally Fig 4 suggests that MAGICC provides better agreement with observations than CM3 does. Similar to reviewer #1 I would suggest putting more focus on the fact that it is difficult to evaluate simplified models by complex models with large variability. In addition some possible ways to overcome this problem could be provided, e.g. larger number of ensembles or simulations with a quasi-chemistry-transport model mode (e.g. Deckert et al., 2011). Publikation: Deckert, Rudolf und Jöckel, Patrick und Grewe, Volker und Gottschaldt, Klaus-Dirk und Hoor, Peter (2011) A quasi chemistry-transport model mode for EMAC. Geoscientific Model Development, 4, Seiten 195-206. Copernicus Publcations. DOI: 10.5194/gmd-4-195-2011 ISSN 1991-959X DOI: 10.5194/gmd-4-195-2011 ISSN 1991-959X

Response: We thank the referee for the constructive and thoughtful feedback, and have made a lot of changes in response to these comments and related comments by Reviewer #1. Broad changes throughout the text include:

- more emphasis on unforced variability as an additional reason why simplified models are preferred tools for impacts of small changes;
- text modifications to caveat the difficulty in comparing simple model results with more complex models;
- discussion of unforced variability in AM3/CM3 expanded and moved to the beginning of the results section rather than the end;
- an additional simulation to isolate unforced variability in AM3, and the results added to the figure with the CM3 control run;
- text modifications to reduce the impression that CM3 is "truth;" and
- addition of strategies to overcome the challenge of unforced variability.

Comment 2: For my opinion the description of the models and simulations should be more detailed. I had for example some difficulties to exactly understand what the models use as an input and which parameter were calculated by the models.

- Are the concentrations (p4-l1) or the emissions (p4-l7) prescribed in MAGICC?

Response: Concentrations are prescribed through 2005 in MAGICC, and then emissions drive the model. This is clarified in the text (lines 7-23 – 7-25): "*(Note that the updated atmospheric lifetime only impacts the model from 2006-2014 as it is driven by emissions and not concentrations during this period.)"* And (lines 9-2 – 9-4): *"(Note that concentrations are prescribed for MAGICC only through 2005, and then emissions inputs drive the model thereafter; however, the resulting concentrations from these emissions are consistent with that input into CM3.)"*

- Was the choice of the ensemble members of CM3 randomly or did you choose years with extreme or mean values?

Response: The CM3 ensemble members were chosen stochastically. We have clarified this in the text.

- How is the RF calculated in CM3?

Response: The basic shortwave and longwave radiation algorithms used in CM3 are described in Freidenreich and Ramaswamy (1999) and Schwarzkopf and Ramaswamy (1999), respectively, modified as in GAMDT (2004) to enhance computational efficiency. The shortwave algorithm includes 18 bands in the solar spectrum, and the longwave algorithm includes eight bands. Shortwave radiation parameterizations account for absorption by water vapor, carbon dioxide, ozone, molecular oxygen; molecular scattering; and absorption and scattering by aerosols and clouds. The longwave radiation parameterizations account for absorption and emission by water vapor, carbon dioxide, ozone, nitrous oxide, methane, halocarbons (CFC-11, CFC-12, CFC-13 and HCFC-22), aerosols, and clouds. Aerosols included are sulfate, carbonaceous (black and organic carbon), dust, and sea salt. Indirect effects of aerosols on clouds are included, and sulfate and black carbon are assumed to be homogenously mixed. We have added these details to the text. However, in this study, we calculate radiative forcings using the atmosphere-only component of CM3—AM3. We do this to calculate RFs that are most similar in definition to that by MAGICC. We therefore use AM3 to diagnose transient effective radiative forcing (ERF) (the change in net radiation balance at the top-of-atmosphere (TOA) following a perturbation to the climate system taking into account any rapid adjustments (Myhre et al., 2013)) due to CO2 and methane.

Additions to text include (lines 6-28 – 7-3): "*Shortwave and longwave radiation algorithms in CM3 are described in Freidenreich and Ramaswamy (1999) and Schwarzkopf and Ramaswamy (1999), respectively, with some modification to enhance computational efficiency (GAMDT 2004). The shortwave algorithm includes 18 bands in the solar spectrum, and the longwave algorithm includes eight bands. Shortwave*

radiation parameterizations account for absorption by water vapor, carbon dioxide, ozone, molecular oxygen; molecular scattering; and absorption and scattering by aerosols and clouds. The longwave radiation parameterizations account for absorption and emission by water vapor, carbon dioxide, ozone, nitrous oxide, methane, halocarbons (CFC-11, CFC-12, CFC-13 and HCFC-22), aerosols, and clouds. Aerosols included are sulfate, carbonaceous (black and organic carbon), dust, and sea salt."

Freidenreich, S.M. and V. Ramaswamy (1999), A new multiple-band solar radiative parameterization for general circulation models, J. Geophys. Res., 104, 31, 389-31, 409.

Geophysical Fluid Dynamics Laboratory Global Atmospheric Model Development Team (GAMDT) (2004), The new GFDL global atmosphere and land model AM2-LM2: Evaluation with prescribed SST simulations, J. Clim., 17(24), 4641-4673.

Schwarzkopf, M. D. and V. Ramaswamy (1999), Radiative effects of CH4, N2O, halocarbons and the foreign-broadened H2O continuum: A GCM experiment, J. Geophys. Res., 104, 9467-9488

- Why does All Forcing in MAGICC have a large variability, while the CO2 and CH4 do not have one? Are the forcings (except CO2 and CH4) prescribed?

  Response: The All Forcing variability in MAGICC is due to prescribed forcings from volcanic eruptions.

- Why does CO2 show negative Forcing in Fig 2 although the concentration increases?

  Response: This is most likely due to unforced variability in AM3, from a mixture of land snow/ice cover variability and just year-to-year variability in the weather; soil moisture may also play a role. An additional simulation that we performed to assess the magnitude of unforced variability in AM3 revealed that Radiative forcings at the top-of-atmosphere for all-sky conditions can yield annual swings of 0.8 W m-2, and 5-yr running means dampen this to around 0.35 W m-2. Decadal swings are around 0.2 W m-2. The negative forcings despite increased concentrations falls within the realm of expected variability.

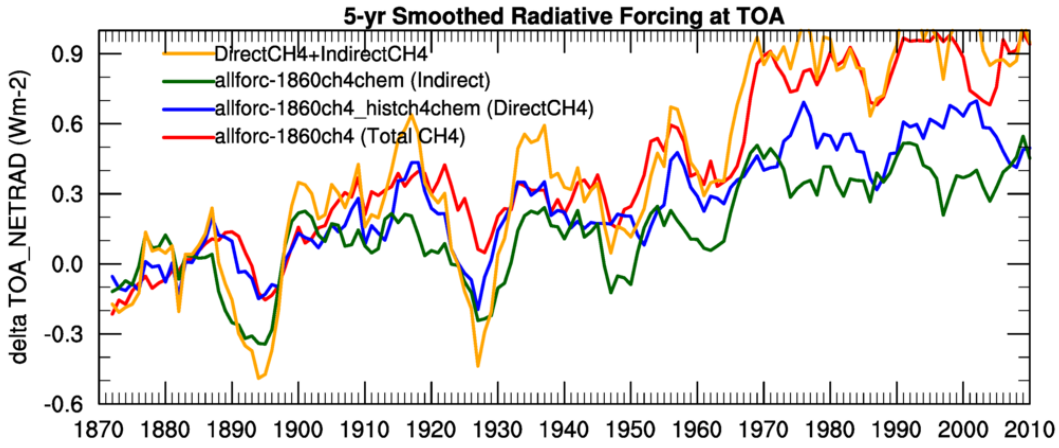
- Why are direct and indirect CH4 effects anti-correlated or have a time lag? Is there a physical explanation or is it an artifact of the internal variability?

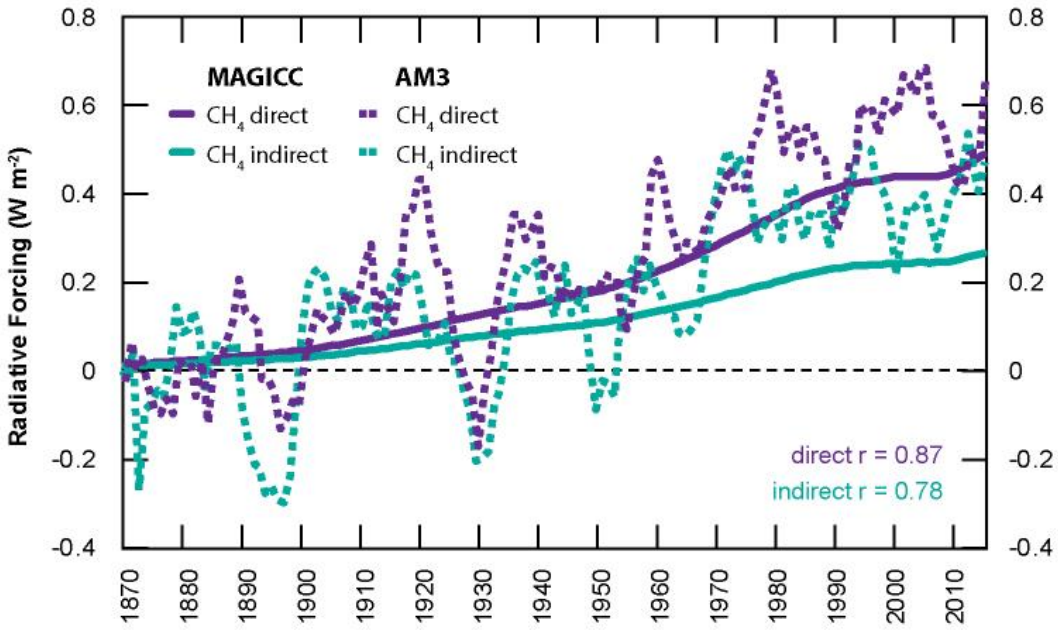
  Response: We have determined that the anti-correlation and other unusual features in the figure were almost entirely due to our methodology of

double subtraction to calculate indirect methane forcings in AM3 from the CH4-only and direct CH4 forcings.

We determined this via running additional simulations to calculate the indirect methane forcings and responses via modifications to chemistry rather than our original method that introduced a double subtraction to determine the indirect effects. We ran AM3 and all ensemble members of CM3 for an experiment where methane radiation varied with time but chemistry was held at 1860 methane levels.

We have therefore updated the manuscript to reflect this new methodology for indirect effects of methane, keeping the original methodology for direct effects of methane. This method is also more consistent with how we calculated indirect effects of methane in MAGICC. While the direct and indirect effects are not completely additive (see figure below) this is typical nonlinearity effects for models of this complexity.





- Why is the temperature change of CH4 of CM3 negative although the forcing is positive?

  Response: Similar to CO2 forcings in the former Fig. 2, temperature responses to methane can be negative despite positive forcings due to unforced variability in CM3. We find that unforced internal dynamics (interaction among the ocean-atmosphere-land system) in CM3 introduce yearly temperature swings of 0.09 °C on average (though it can be as high as 0.4 °C), and this drops to 0.02 °C on average when five-year running means are employed (at most 0.2 °C) on average. The negative temperature responses to CH4 fall within this realm of variability. We have added text throughout the paper to discuss the role of unforced variability in influencing the results, making it difficult to compare MAGICC with CM3 and also providing more justification for why a model like MAGICC is needed.

- p6-l5 MAGICC simulates from 1750-2100, but in p4-l1-9 only information about concentrations and forcings between 1765 and 2014 are given

  Response: We have edited the text to explain that emissions drive the model from 2005-2100 but that we restrict our analysis here through 2014.

- P6 l21 Does the 'downloaded' version of MAGICC include tuning to the multi-model mean or can be chosen which AOGCM is used for calibration?

Response: The downloaded version of MAGICC allows for tuning of parameters, and one can choose which AOGCM parameters to employ. We have clarified this in the text (lines 5-24 – 5-25): "*The user of the downloaded MAGICC model can select which parameters to use for each simulation.*"

- P8-25 A description about the kind of data used should be included

Response: We have clarified this in the text (lines 11-22 – 11-25): "*Figure 5 shows the historical global-mean surface air temperature responses to changes in all-forcings in MAGICC and CM3 compared with NOAA and National Aeronautics and Space Administration (NASA) time series of global surface temperature anomalies data, freely available online (https://www.ncdc.noaa.gov/cag/time-series/global and https://data.giss.nasa.gov/gistemp/).*"

Comment 3: Technical comments

P5-l12 comma is missing after carbon dioxide

Response: We have made this change.

P6-29 Here RF is defined at the tropopause, while it is defined at the top of the atmosphere in p7-23

Response: We thank the referee for catching this error and we have corrected it.

P8-3 change 'slightly offset' in âA˘ Žoffset' (1W/m2 is large compared to the forcing)

Response: We have made this change.

P11-1 change 'accurately' in 'adequately'

Response: We have made this change.

Is there a reason why the Fig starts in different years (1860, 1870 or 1880)?

Response: Yes. The CM3 climate model runs start in 1860, but the AM3 forcing runs start in 1870 due to constraints by the prescribed SST observations. Observational data for global surface air temperature begins in 1880.

Responses to SC1 (Marcus Sarofim):

Comment 1: MAGICC is, of course, one of the most widely used tools for this purpose, and therefore a reasonable choice. However, it might be worthwhile for the authors to discuss a couple of alternatives.

a. Hector is in a similar class of model as MAGICC, but has the advantage of being fully open-source (see comment on 11-21 from Referee 1). Hector is described in Hartin et al. 2014, https://core.ac.uk/download/pdf/25503085.pdf. Also relevant is a thesis by Schwarber on comparing Hector and MAGICC at https://www.atmos.umd.edu/theses_archive/2016/aschwarber_masters.pdf. I am not suggesting running Hector for this paper, as that would be a large lift, but a citation and brief mention of the benefits of open source could be worthwhile.

b. Meanwhile, there are approaches that are even simpler than MAGICC. Melvin et al. (2016), for example, estimated the physical impacts resulting from methane mitigation by using the simplified expressions from AR5 for concentration and radiative forcing and from Shine et al. (2005) for temperature. It could be a valuable sensitivity analysis to take one of these simplified approaches as an additional comparison. These simplified equations may be better suited to analyzing the marginal effect of perturbations in emissions, rather than to simulate overall global temperature change from total anthropogenic emissions: however, it seems to me that this kind of marginal analysis is consistent with the goals of this paper.

c. The NAS in their report on valuing climate damages (https://www.nap.edu/catalog/24651/valuing-climate-damages-updating-estimationof-the-social-cost-of) suggest the use of the FAIR model: this would fall between Hector/MAGICC and the GTP-style equations in terms of complexity.

> **Response:** We thank the reviewer for the thoughtful comments and additional information. We have added text to acknowledge the other tools that exist with complexity levels between GWP and GCMs, with the above references, and have made it clear that MAGICC is not the only tool in its class. However, we do note that none of the above options seem appropriate for our particular analysis: Hector does not explicitly calculate concentrations of methane, and uses input files instead; GTP expressions, which we have used previously and compared with MAGICC, do not allow for a changing atmospheric lifetime in response to changing OH concentrations – a critical feedback for methane impacts; and finally, the FAIR model goes beyond the climate indicators we are interested in, by including a cost sub-model to look at economic parameters. Therefore, we did not include specific details about these tools in the text.

Comment 2: As with Referee 1, I find it surprising that the AM3 forcing results only diverge in the last couple decades in contrast with MAGICC which shows a slowly growing divergence over the entire run. Would there be any effect of running AM3 with different initial conditions, which could show whether this is a robust result or a result

deriving from internal variability? The only other explanation that comes to mind other than initial condition sensitivity is that somehow CO2 and CH4 forcing have differential sensitivity to SSTs or sea-ice extent. Maybe a constant-concentration experiment could be informative in terms of whether the forcing of methane and CO2 might respond differently to the historical changes of SST & sea-ice?

Response: We thank the reviewer for these thoughts. We ran an additional simulation with constant preindustrial (1860) external radiative forcings and repeating seasonal cycle of sea surface temperatures and sea ice characteristics for 200 years for AM3 in order to assess the role of unforced variability. Analysis revealed that radiative forcings at the top-of-atmosphere for all-sky conditions can yield annual swings of 0.8 W m-2, and 5-yr running means dampen this to around 0.35 W m-2. Decadal swings are around 0.2 W m-2. Therefore, the CO2 and methane forcing swings, especially at smaller forcings, fall within the realm of variability and therefore cannot be considered a robust feature. We have added this discussion to the text.

Comment 3: I do find this comparison of more complex models to simple models to be an informative exercise (see Sarofim 2012 where I used both the MIT IGSM and MAGICC to calculate the 100-year sustained GTP for methane: https://link.springer.com/content/pdf/10.1007%2Fs10666-011-9287-x.pdf). But, as Referee 1 notes, this comparison is complicated by the variability inherent in more complex models, even as at the same time, this is one of the motivators behind the use of simple models for investigating the effect of emissions perturbations that are expected to have temperature effects smaller than the internal variability of the complex models. I don't have a good answer for this, other than averaging even larger ensembles in order to reduce initial-condition-based noise even more.

Response: We wholeheartedly agree with the reviewer. We have substantially expanded our discussion and analysis of the role of unforced variability in not just this analysis, but in comparison between simple and more complex models in general. We also addressed more directly the fact that this is indeed a major motivation for using simpler models for smaller forcing changes. With present computational resources, more ensemble members to diagnose multiple individual forcings and resulting temperature responses is not feasible. However, despite temperature swings in CM3 unparalleled by MAGICC, the general trends and magnitudes are fairly consistent, providing confidence in our use of MAGICC going forward.

Rapid and reliable assessment of methane impacts on climate

Ilissa B. Ocko[1], Vaishali Naik[2] and David Paynter[2]

[1]Environmental Defense Fund, Washington DC, 20009, USA
[2]NOAA Geophysical Fluid Dynamics Laboratory, Princeton, 08540, USA

Correspondence to: Ilissa B. Ocko (iocko@edf.org)

Abstract. It is clear that the most effective way to limit global temperature rise and associated impacts is to reduce human emissions of greenhouse gases, including methane. However, quantification of the climate benefits of mitigation options are complicated by the contrast in the timescales at which short-lived climate pollutants, such as methane, persist in the atmosphere as compared to carbon dioxide. Whereas simple metrics fail to capture the differential impacts across all timescales, sophisticated climate models that can address these temporal dynamics are often inaccessible, time-intensive, ~~and~~ require special infrastructure, and include high unforced interannual variability that makes it difficult to analyse small changes in forcings. Reduced-complexity climate models offer an ideal compromise in that they provide quick, reliable insights into climate responses~~the benefits across types of~~ to relatively small changes in forcings of different climate pollutants, due to the absence of strong internal variability, using basic knowledge and limited computational infrastructure. In this paper, we build on previous evaluations of the freely-available and easy-to-run reduced-complexity climate model MAGICC by ~~confirming~~ comparing ~~its ability to reproduce~~ temperature responses to historical methane emissions to~~. By comparing MAGICC model results to~~ those from ~~the reference~~a more complex ~~GFDL CM3~~ coupled global chemistry-climate model, GFDL CM3.~~, we build confidence in using MAGICC for purposes of understanding the climate implications of methane mitigation.~~ While we find that the overall forcings and temperature responses are comparable between the two models, the prominent role of unforced variability in CM3 demonstrates how sophisticated models are potentially inappropriate tools for small forcing scenarios. On the other hand, we find that MAGICC can easily and rapidly provide robust data on climate responses to changes in methane emissions with clear signals unfettered by variability. We are therefore able to build confidence in using MAGICC for purposes of understanding the climate implications of methane mitigation.

1 Introduction

Reduced-complexity climate models offer an ideal framework for evaluating greenhouse gas mitigation options if they can accessibly and rapidly reproduce the results of the more complex global chemistry-climate models (CCMs) that include more advanced and comprehensive treatments of chemistry and physics (Meinshausen et al., 2011a). However, there is a critical need to build confidence in the ability of reduced-complexity models to simulate temperature responses to individual

greenhouse gases rather than just the suite of climate pollutants, because greenhouse gases have vastly different radiative properties and atmospheric lifetimes (Myhre et al., 2013; Fiore et al., 2015); it is important to confirm that individual species are represented appropriately if reduced-complexity models are to serve as an effective tool for assessing climate benefits of mitigation actions. This is especially central for the analysis of methane (CH_4) mitigation actions, of which the climate policy community has been increasingly ~~interested in pursuing~~focused on (e.g., ~~Alvarez et al., 2012;~~ Shindell et al., 2012; Collins et al., 2018). Therefore, this paper builds on previous evaluations by comparing forcing and temperature responses to historical methane and carbon dioxide (CO_2) concentrations from a widely-used reduced-complexity climate model, with that from a state-of-the-art coupled global chemistry-climate model. While it is difficult to compare climate responses of simple models with that of complex ones because of the presence of unforced variability in the latter, ~~W~~we ultimately seek to determine if general temporal patterns and magnitudes are consistent enough to justify the use of a reduced-complexity climate model ~~can be a~~ as a ~~useful and~~ reliable tool for rapid assessment of methane mitigation measures.

~~Given that c~~Climate change impacts have now been observed on every continent and in every ocean (Stocker et al., 2013)~~.~~, If we want to reduce~~ing~~ near- and long-term anthropogenically caused warming, then we need to reduce emissions of several climate pollutants ~~is urgent~~. While limiting long-term climate warming requires drastically reducing CO_2 emissions, reducing emissions of short-lived climate pollutants (SLCPs)—specifically, methane and black carbon (BC)—has~~ve~~ been identified as one of the most effective ways to reduce near-term warming (e.g., Ramanathan and Xu, 2010; Shindell et al., 2012; Rogelj et al., 2013; Shoemaker et al., 2013). Methane emissions in particular account for a quarter of the excess energy trapped by human emissions, and today's global anthropogenic methane emissions will have a larger impact on near-term warming than today's global fossil fuel CO_2 emissions (based on forcing data provided in Myhre et al., 2013 and references therein; methane emissions provided in EPA, 2012; CO_2 emissions provided in IEA, 2015; and radiative efficiency estimates of methane provided in Etminan et al., 2016). Sustained methane emissions will also impact long-term warming (Allen et al., 2016). Furthermore, reducing methane emissions has air quality~~, and~~ health, and food security co-benefits (Shindell et al., 2012; West et al., 2013; Zhang et al., 2016; Melvin et al., 2016).

Most methane mitigation measures are assessed as a comparison to carbon dioxide warming impacts; almost all policy analyses rely on the simple metric Global Warming Potential (GWP) because of its simplicity and ease of use (Ocko et al., 2017). However, GWP is limited in its ability to quantify climate effects because it relies on the integrated impact of a pulse of emissions over a specified time horizon. Because methane and CO_2 have vastly different atmospheric lifetimes, their respective climate impacts occur over different timescales~~, and~~ Due to the inherent selection of a single time horizon, GWP is incapable of capturing these important temporal distinctions (e.g., Solomon et al. 2010; Alvarez et al., 2012) unless two time horizons that represent near- and long-term impacts are reported simultaneously (Ocko et al., 2017).

Assessment of SLCP climate impacts over different timescales can be performed using comprehensive global chemistry-climate models (CCMs), however, a full assessment of various SLCP ~~mitigation~~ scenarios using sophisticated CCMs is

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computationally intensive and time-consuming. and forcing perturbations from slight changes in individual species are often too small for the response signal to be detected among the high unforced internal climate variability present in CCMs (e.g., Ocko et al., 2014).~~.~~ Determining robust climate responses to small-forcing ~~a specific mitigation~~ scenarios using CCMs therefore requires a large number of ensemble simulations (Deser et al., 2012)~~. and forcing perturbations of specific mitigation scenarios are often too small for the response signal to be detected among internal climate variability. Further,~~ Given that many institutions do not have access to CCMs nor the technical capacity or expertise to run these models~~. Therefore~~, they must rely on partnerships with ~~modeling~~modelling ~~centers~~centres that are often focused on model development. ~~This~~ These characteristics of CCMs reinforces the use of the simple GWP metric for assessments of climate pollutant mitigation measures.

While detailed assessment of regional climate responses can only be provided by complex CCMs, reduced-complexity climate models offer a useful alternative for global changes in major climate characteristics that is far more advanced than GWP but avoids ~~To avoid~~ the need for the tremendous amount of computational resources required to perform CCM simulations (and especially with enough ensemble members to average out unforced variability). These simpler models can rapidly analyse global average climate responses because they are easily accessible and quick to run, thereby~~and to rapidly~~ providinge immediate scientific guidance for mitigation ~~decisions~~assessments. Further, because they do not include unforced internal variability, they provide clear responses to small forcing scenarios without any noise. ~~, one option is to use reduced-complexity climate models~~. ~~While detailed assessment of regional climate responses can only be provided by complex CCMs, the simpler models are ideal for analyzing global average climate responses, because they are easily accessible and quick.~~

There are several models that have been developed that fall within this intermediate complexity class—more advanced than simple metrics but far less sophisticated than CCMs. They range from simplified expressions (e.g., Shine et al. 2005) to more complex chemistry and physics but computations of only a few climate indicators averaged over large spatial domains (e.g., Meinshausen et al. 2011a; Hartin et al. 2014). One ~~such model~~of the latter is the freely available Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC), initially developed in the late 1980s (Wigley and Rapper, 1987, 1992) and routinely updated since (e.g., Meinshausen et al., 2011a). While not meant to replace atmosphere-ocean global climate models (AOGCMs) and carbon cycle models, MAGICC is a complementary, computationally-inexpensive tool that is capable of efficiently ~~analyzing~~analysing basic climate responses (such as radiative forcing, surface air temperature, and ocean heat uptake) to a suite of emission scenarios. Confidence in MAGICC results comes from a comprehensive effort to match several AOGCMs and carbon cycle models (Meinshausen et al., 2008, 2011a). Evaluations show that MAGICC closely reproduces temperature responses to aggregated forcings from the sophisticated Coupled Model Intercomparison Project CMIP3 atmosphere-ocean and C4MIP carbon cycle models (Meinshausen et al., 2011c).

While not the only model of its class, ~~T~~the reduced complexity model MAGICC is ~~therefore a~~n especially great resource for mitigation analysis because of its widespread use in international climate reports, and the ability of the user to modify future emissions of every radiatively active species. Therefore, when ~~where~~ numerous scenarios exist and need to be evaluated ~~before~~ for decision-making, a rapid tool like MAGICC can provide rapid insight into the climate impacts of various options. However,

~~T~~to build confidence in MAGICC's evaluation of greenhouse gas mitigation strategies, we need to adequately assess its ability to reproduce climate responses to individual greenhouse gases beyond the aggregated forcings. Here, we ~~analyze~~analyse the capability of MAGICC in simulating climate responses to historical increases (1860-2014) in methane and CO_2 by comparing the results with that from a state-of-the-art coupled chemistry-climate model, the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL) CM3 model, which has been shown to adequately reproduce historical temperature trends (Golaz et al. 2013, Griffies et al., 2011; Donner et al., 2011; Winton et al., 2012; John et al., 2012; Levy et al., 2013). While it is difficult to compare simpler models with sophisticated ones for scenarios with small forcings – due to high interannual variability built into the latter – it is nevertheless important to do so because of the more advanced and comprehensive chemistry and physics in the more complex models.

~~Our goal is to build confidence in the simulation of the climate response to methane in order to justify future use of MAGICC to assess the climate impact of methane emissions mitigation scenarios.~~ We compare the response of the two models to assess similarities and differences, seeking to determine (i) if the forcings/temperature response comparable; (ii) if the complexity of the CCM provides any benefits over the simple model; and (iii) does the lack of variability in the simple model provide any advantages over the CCM when looking at small forcing amounts. Our goal is to build confidence in the simulation of the climate response to methane in order to justify future use of MAGICC to assess the climate impact of methane emissions mitigation scenarios. In this analysis, ~~W~~we add to previous evaluations by showing a high correlation between CM3's and MAGICC's radiative forcing and surface air temperature responses to changes in either CO_2 or methane in isolation, despite large unforced variability in CM3, thereby strengthening confidence in MAGICC's simulation of climate responses to individual greenhouse gases with vastly different radiative properties and lifetimes.

2 Models and Simulations

2.1 MAGICC model description

We use MAGICC v.6 version developed in 2011 (http://www.magicc.org/download). MAGICC represents the complex coupled carbon-cycle climate system as a hemispherically averaged upwelling-diffusion ocean coupled to an atmosphere layer and a globally averaged carbon cycle model. The atmosphere has four boxes (one over land and one over ocean for each hemisphere) and is coupled to the mixed layer of the ocean hemispheres. The default number of ocean layers in each hemisphere is 50 including the mixed layer (though users can select the number of levels), and heat exchange is driven by vertical diffusion and advection. The terrestrial carbon cycle model is a globally integrated box model with one living plant box and two dead biomass boxes (one for detritus and one for organic matter in soils). The terrestrial carbon cycle does not feedback into carbon dioxide concentrations in the atmosphere. The sea-to-air carbon flux is determined by the partial pressure differential for carbon dioxide between the atmosphere and surface layer of the ocean.

From 1765–2005, the MAGICC v.6 radiative forcing is driven by global-mean concentrations of greenhouse gases (carbon dioxide, methane, nitrous oxide, ozone-depleting substances and their replacements); prescribed regional direct aerosol radiative forcings (~~sulfate~~sulphate, black and organic carbon, sea salt, mineral dust); land-use, volcanic, and solar radiative forcings; prescribed black carbon on snow radiative forcings; emissions of tropospheric ozone precursors (carbon monoxide, nitrogen oxides, non-methane volatile organic carbon); and indirect (first and second) aerosol forcings calculated from prescribed regional aerosol optical depths (parameterizations described in detail in Meinshausen et al. (2011a)). For 2006 to 2014, the model is driven by emissions of gases and aerosols taken from the Representative Concentration Pathway (RCP8.5) scenario to capture a business-as-usual trajectory. Climate responses (such as surface air temperature) are provided as global annual averages and also across four spatial boxes (over land and ocean and by hemisphere).

Historical greenhouse gas concentrations are from Meinshausen et al. (2011b); prescribed aerosol forcings and land-use historical forcings are from the National Aeronautics and Space Administration (NASA) GISS model (http://data.giss.nasa.gov/); solar irradiance is provided by Lean et al. (2010); and historical emissions of ozone precursors are from Lamarque et al. (2010). Present-day ~~(2005–2014)~~ and future (2005–2100) forcings are driven by emissions of gases and aerosols, and are taken from the Representative Concentration Pathway (RCP8.5) scenario to capture a business-as-usual trajectory, though we restrict our analysis here to climate responses from 1860–2014. Carbon dioxide ~~and methane~~ radiative forcings are calculated using a standard simplified expression~~s~~ (Shine et al. 1990~~;~~ with updated scaling parameter from Myhre et al. 1998). Methane radiative forcings are calculated using a radiative efficiency parameter in conjunction with standard simplified expressions from Myhre et al. (1998), and accounts for overlap between methane and nitrous oxide absorption bands.

For the most recent version of MAGICC, seven key climate parameters were calibrated to match 19 AOGCMs used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report AR4 (see Meinshausen et al., 2011a). The parameters include: equilibrium climate sensitivity, land-ocean warming ratio at equilibrium, vertical diffusivity in the ocean, sensitivity of feedback factors to radiative forcing change, sensitivity of vertical diffusivity at mixed layer boundary to global-mean surface temperatures (i.e., thermal stratification), land-ocean heat exchange coefficient, and an amplification factor for the ocean to land heat exchange. The MAGICC parameter set that best reproduces surface air temperatures and heat uptake of each AOGCM is determined via an optimization routine with 1000 iterations to find the combination that minimizes the squared differences between low-pass filtered time series. The effective climate sensitivities in MAGICC v.6 vary over time due to spatially non-homogenous varying feedbacks, until they reach the equilibrium climate sensitivity. The equilibrium climate sensitivity input into MAGICC depends on which AOGCM calibration is used; they range from 1.9 to 5.73 °C across all 19 models, with a mean (median) of 2.88 °C (2.59 °C). Multi-model-ensembles are generated by running each simulation for all 19 AOGCM calibrations, which we refer to as "physics-driven ensemble members." ~~–~~ The user of the downloaded MAGICC model can select which parameters to use for each simulation.

While the MAGICC model is particularly well-calibrated to more sophisticated models, the realism of MAGICC results relies on the realism of GCMs, which have their own sets of limits and uncertainties. Further limitations of MAGICC include incomplete knowledge of forcing patterns, unknown responses outside of the calibrated range, limited set of climate responses evaluated (such as temperature and heat uptake but not precipitation), reliance on a high level of parametrization (such as cloud feedbacks tuned to match those of more sophisticated GCMs), and possible errors in the data used for calibration. However, despite these limitations, MAGICC has been shown to reasonably reproduce climate responses to all-forcing scenarios (Meinshausen et al., 2011a).

2.2 CM3 model description

We employ the GFDL global coupled atmosphere-ocean-chemistry model (GFDL-CM3; Donner et al., 2011; Griffies et al., 2011) to assess the climate response to historical changes in methane and CO_2. CM3 uses a finite-volume dynamical core on a cubed-sphere horizontal grid composed of six faces; each face includes 48 × 48 grid cells. The size of the grid cells range from 163 km at the corners to 231 km near the face ~~centers~~centres. In the vertical, the model domain extends from the surface up to 0.01 hPa (86 km) with 48 vertical hybrid sigma pressure levels. The model simulates tropospheric and stratospheric chemistry interactively over the full vertical domain, with simulated ozone and aerosols influencing radiation calculations (Naik et al., 2013; Austin et al., 2013). Ensemble members for CM3 are generated by employing different sets of stochastically-selected initial conditions (discussed in more detail in Sect. 2.3.), which we refer herein as "initial condition-driven ensemble members." The equilibrium climate sensitivity of CM3 is 4.8 K (Paynter et al., 2018), which is higher than that of MAGICC.

Global mean concentrations of well-mixed greenhouse gases (WMGHGs), including carbon dioxide, nitrous oxide, methane, and ozone-depleting substances (ODSs) are specified for radiation calculations for the historical period (1860-2005) from Meinshausen et al. (2011b) and for the period 2006 to 2014 following the Representative Concentration Pathway (RCP8.5) scenario. Within the chemistry module, global mean concentrations of methane are prescribed at the surface as the lower boundary condition and are allowed to undergo chemistry everywhere else in the model domain. Radiation calculations do not see the full three-dimensional methane field (simulated in the chemistry module) and only employ the global-mean concentrations, however, changes in ozone and water ~~vapor~~vapour are seen by the radiation. ~~CM3 does not capture~~Further, CM3 CO_2 concentrations do not get altered by reactions that occur in the model. ~~the indirect feedbacks on carbon dioxide from methane.~~

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CM3 is forced with emissions of short-lived species including ozone precursors, and aerosols and their precursors, volcanic aerosols, solar radiation, and land-use change as described in detail by Donner et al. (2011) and Naik et al. (2013). Anthropogenic emissions, including from biomass burning and ships, for the time period 1860–2005 are from the dataset of Lamarque et al. (2010) developed in support of the Couple Model Intercomparison Project Phase 5 (CMIP5). For years 2006–2014, anthropogenic emissions follow the RCP8.5 scenario. Natural emissions of all precursor species, except isoprene, are included as described by Naik et al. (2013). Biogenic isoprene emissions are calculated interactively, as described by Lin et

al. (2012), based on the Model of Emissions of Gases and Aerosols in Nature (MEGAN) (Guenther et al., 2012). 'Explosive' volcanic eruptions are imposed via a time series of volcanic optical properties rather than from direct injection of sulphur into the stratosphere (Stenchikov et al., 2006; Donner et al., 2011).

Shortwave and longwave radiation algorithms in CM3 are described in Freidenreich and Ramaswamy (1999) and Schwarzkopf and Ramaswamy (1999), respectively, with some modification to enhance computational efficiency (GAMDT 2004). The shortwave algorithm includes 18 bands in the solar spectrum, and the longwave algorithm includes eight bands. Shortwave radiation parameterizations account for absorption by water vapour, carbon dioxide, ozone, molecular oxygen; molecular scattering; and absorption and scattering by aerosols and clouds. The longwave radiation parameterizations account for absorption and emission by water vapour, carbon dioxide, ozone, nitrous oxide, methane, halocarbons (CFC-11, CFC-12, CFC-13 and HCFC-22), aerosols, and clouds. Aerosols included are sulphate, carbonaceous (black and organic carbon), dust, and sea salt.

CM3 includes explicit representation of both the direct and indirect aerosol effects on radiation. For the calculation of the direct effect of aerosols on radiation, physical and optical properties of ~~sulfate~~sulphate, black carbon, organic carbon, sea salt, and dust are considered in the model (Donner et al., 2011). ~~Sulfate~~Sulphate and black carbon are assumed to be internally mixed while all other aerosols are assumed to be externally mixed for radiation calculations. To account for the indirect effect of aerosols via aerosol-water cloud interactions, the model treats water soluble aerosols, including sea salt, and organic aerosols as cloud-condensation nuclei (CCN) allowing a physically based parameterization of CCN activation (Ming et al., 2006). The model does not consider the reduction in surface albedo caused by the deposition of ~~BC~~ black carbon on snow-covered surfaces.

2.3~~.~~ Simulations

~~Four~~ Three historical simulations are run for both MAGICC and GFDL CM3 to derive climate responses to isolated CO_2 and methane concentrations, respectively~~, and to parse out direct from indirect warming effects of methane~~. MAGICC was run from 1750 to 2100 by default, and CM3 was run from 1860 to 2014. As shown in Table 1, the direct runs for both models include an all-forcing simulation with all forcings varying with time except land-use; a simulation with CO_2 concentrations held at 1860 levels; and a simulation with methane concentrations held at 1860 levels. Subtracting temperature responses of the two latter runs from the former yield CO_2-only and methane-only climate responses, respectively (see Eqs. (1) and (2). The same equations hold for the forcings as well.

$$\Delta T_{CO2} = T_{All~~F~~-~~f~~orc~~ing~~} - T_{CO2=1860}\,, \quad (1)$$

$$\Delta T_{CH4} = T_{All~~F~~-~~f~~orc~~ing~~} - T_{CH4=1860}\,, \quad (2)$$

For MAGICC, each simulation is run for all 19 AOGCM-calibrated configurations; each 350-year integration took approximately one second to run on a modern PC with a three GHz CPU processing speed. We use default MAGICC gas and aerosol properties, but update methane and tropospheric ozone radiative efficiencies and methane atmospheric lifetime to IPCC Fifth Assessment Report (AR5) values (Myhre et al., 2013; Stevenson et al., 2013) to reflect the latest science. (Note that the updated atmospheric lifetime only impacts the model from 2006-2014 as it is driven by emissions and not concentrations during this period.) However, we do not include newer estimates of methane radiative efficiency that account for shortwave absorption in addition to longwave absorption (Etminan et al., 2016) to be consistent with the CM3 model that only includes longwave effects. Including the shortwave component increases methane's radiative efficiency by over 20%. Further, we specifically do not tune MAGICC model climate and forcing properties to match that of CM3 because we are assessing how a "standard version" of the reduced-complexity climate model compares with CM3; the goal is not to match MAGICC to CM3 but to assess whether a downloaded version of MAGICC broadly behaves similarly to CM3. However, two of MAGICC's physics-driven ensemble members are derived from two predecessors of CM3: CM2.0 and CM2.1 (Delworth et al., 2006).

The set-up of GFDL-CM3 simulations conducted here was similar to that adopted for simulations performed in support of the CMIP5, except we obtained initial conditions from a longer preindustrial control (3000 years). Three-member initial condition-driven ensembles of transient CM3 simulations were performed with each ensemble member initialized stochastically at different points in the preindustrial control simulation. Each 155-year integration of CM3 took about 15 days to complete on the NOAA's Remotely Deployed High Performance Computing System (RDHPCS) machine known as "Gaea" running on 464 processors. While three ensemble members is relatively small, we are limited by computational resources and studies have shown that forced changes in air temperature, as opposed to changes in atmospheric circulation and precipitation, can be detected with fewer ensemble members (Deser et al., 2012).

To compute CM3 radiative forcings for CO_2 and methane (direct and indirect) that are closest to the definition used by MAGICC (the forcing at the tropopause after stratospheric temperature adjustment), we performed simulations with the atmosphere-only version of CM3—AM3. The model configuration of AM3 was exactly the same as CM3 except AM3 model integrations over the period 1870 to 2014 were performed with observed sea-surface temperature and sea-ice cover (Rayner et al., 2003), and therefore do not include an ensemble driven by different initial conditions. Through the additional AM3 simulations, we were able to diagnose transient effective radiative forcing (ERF) (the change in net radiation balance at the top-of-atmosphere (TOA) following a perturbation to the climate system taking into account any rapid adjustments (Myhre et al., 2013)) due to CO_2 and methane. Transient ERF calculated in this way follow the proposed protocol for the AerChemMIP (Collins et al., 2016). ~~While ERF calculated in this way eliminates the need to perform multiple time-slice integrations to assess the trends, it does not reflect the dependence of methane forcing on nitrous oxide concentration due to spectral overlap and likely underestimates the methane ERF (Forster et al., 2016).~~

To separate the effect of methane due to its influence on ozone and water ~~vapor~~vapour (indirect effects) from its effect on radiation (direct effect), we ran two more simulations for MAGICC with methane chemistry turned off (an all-forcing run and

methane held at 1860 levels run with methane chemistry turned off for both). Equation (3) shows how the direct methane forcings were calculated for MAGICC; subtraction between methane-only forcings and the direct forcings yielded the indirect responses to methane., and We also ran two more a simulations for AM3/CM3 with methane radiation calculations or chemistry held constant beyond 1860, respectively. Equations (43) and (54), respectively, show how the indirect and indirect methane forcings were calculated in AM3for both the MAGICC and CM3 models. While we only show forcing calculations here via AM3 simulations with fixed sea surface temperatures, we also ran the simulations for the fully coupled CM3 model.

$$\Delta F_{CH4,indirect\ (MAGICC)} = F_{CH4} - (F_{All-forcing,CH4\text{-}no\text{-}chemistry1860} - F_{CH4=1860,no\text{-}chemistry}) , \quad (3)$$

$$\Delta F_{CH4,direct\ (AM3)} = F_{AllForc} - F_{CH4rad1860} , \quad (4)$$

$$\Delta F_{CH4,indirect\ (AM3)} = F_{AllForcCH4radiation=1860} - F_{CH4chem1860(radiation+chemistry)=1860} , \quad (54)$$

The global mean historical concentrations of CO_2 and methane used by the models to drive bothcalculate radiative forcings and therefore temperature changes models are shown in Fig. 1. (Note that concentrations are prescribed for MAGICC only through 2005, and then emissions inputs drive the model thereafter; however, the resulting concentrations from these emissions are consistent with that input into CM3.) Results for both models are presented as an average of the individual ensemble members (initial condition-driven ensemble members for CM3 and physics-driven ensemble members for MAGICC). Surface air temperatures are taken to be 2 meters above the surface. For both models, we calculate temperature changes as the difference between temperatures in year t compared to that in 1860.

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A key difference between AM3/CM3 and MAGICC is that the full GCM has internally generated unforced variability. This occurs both when the model is coupled (CM3) and run with prescribed sea surface temperatures and sea ice (AM3). The variability can be dampened by applying a smoothing to the annual time-series. However, too long of a smoothing period removes much of the decadal level forcing that we hope to uncover in this study. Therefore, we employ a five-year smoothing average to AM3/CM3 results to filter out some of the internal variability. Additionally, to better quantify and isolate the role of unforced variability in theAM3/CM3, we run control experiments of each with fixed forcing. For CM3 we ran a 500 year control simulation with all radiative forcing held constant at 1860 level. For AM3 we ran a shorter 200 year control run, with all radiative forcing held fixed at 1860 with annually repeating monthly averaged sea surface temperatures and sea ice characteristics taken from 30 years of the CM3 control run.

A key difference between CM3 and MAGICC is CM3's internally generated unforced variability, driven by dynamics of heat exchange within the ocean-atmosphere-land system and internal influences on the energy budget. Therefore, we employ a five-year smoothing average to CM3 results to filter out some of the internal variability.

3 Results and Discussion

Here we analyse AM3/CM3's and MAGICC's radiative forcing and surface air temperature responses to changes in either CO_2 or methane in isolation.

Given that ~~A~~an important ~~major~~ difference between AM3/CM3 and MAGICC results is the role of unforced variability in AM3/CM3, we first analyse the magnitudes of unforced variability in both AM3 and CM3~~n CM3~~. Although initial condition-driven ~~E~~ensemble member means and/or running averages are employed to dampen out some of the variability in AM3/CM3, ~~but~~ it still plays a large role in ~~decadal~~ forcing and temperature responses. CM3, in particular, has been shown to produce magnitudes of variability on the upper end of CMIP5 models (Brown et al., 2015).

~~To isolate the role of unforced variability in CM3, we plot a~~The results of the control simulations with constant preindustrial (1860) external radiative forcings ~~for 500 years~~are shown in ~~(~~Fig. 2~~7~~). In the case of AM3 unforced radiative forcings at the top-of-atmosphere for all-sky conditions range from -0.18 to 0.21 W m^{-2} with a standard deviation of 0.07 W m^{-2} for a five-year running mean. We find the maximum swing between two consecutive five-year means to be 0.35 W m^{-2}. Sources of unforced variability in AM3 include a mixture of land snow/ice cover variability and just year-to-year variability in the weather; soil moisture may also play a role. For CM3, unforced internal dynamics yield temperature responses ranging from -0.27 to 0.24 °C for five-year running means with a standard deviation of 0.1 °C. We find the maximum swing between two consecutive five-year means to be 0.2 °C. The variability is driven by interactions among the ocean-atmosphere-land systems. While unforced variability is a key component to modelling the climate system, it can mask or amplify responses to external forcings over short timescales (e.g., Brown et al., 2017). This makes it difficult to clearly assess responses to small external forcings, and provides further motivation for using simpler models like MAGICC for analysis of small forcing scenarios.

~~Temperature responses from unforced internal dynamics in CM3 introduce decadal temperature swings of 0.5 °C on average.~~

3.1 Radiative Forcing

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Figure 3~~2~~ shows the global-mean ~~top-of-atmosphere (TOA)~~ radiative forcings (RF) in response to the all-forcing scenario as well as forcings attributed to isolated CO_2 and methane concentrations, respectively. Note that AM3 forcings are taken as top-of-atmosphere and include rapid adjustments in the troposphere in addition to the stratosphere, and therefore are considered an effective RF, while MAGICC derived RF is calculated at the tropopause and only considers stratospheric temperature adjustment. MAGICC methane and CO_2 isolated forcings are much smoother than that of AM3 because of the lack of unforced variability in MAGICC. Some unexpected features in AM3 forcings (such as negative forcings in the earlier years despite increasing atmospheric concentrations) are likely due to unforced variability. Using the MAGICC forcings as a benchmark for a signal due to forced changes only, we find that nearly all of the deviations of AM3 fall within the range of internal variability as derived from the control simulation: 0.35 W m^{-2}. However, despite the slightly different forcing definitions and the unforced

variability in AM3, all results are strongly correlated between AM3 and MAGICC (All-forcing r^2 = 0.81, CO_2-only r^2 = 0.96, CH4-only r^2 = 0.93).

In the present-day (model year 2014), AM3 and MAGICC yield an all-forcing RF of 2.0 and 2.5 W m^{-2}, respectively; note that land use is held constant in this analysis. This is consistent with the IPCC (2013) values that show an all-forcing effective RF of 2.3 W m^{-2} in 2011 (Myhre et al., 2013). The magnitudes for the CM3 and MAGICC all-forcing radiative forcings are ~~slightly~~ offset after 1960 (-1 W m^{-2} in 1960). This is due to AM3's strong aerosol indirect forcing (Golaz et al., 2010) beginning around this time when aerosol emissions in the mid-latitudes increased rapidly (Lamarque et al., 2010).

Isolating CO_2 and methane's contribution to overall forcings (Fig. 3), MAGICC is reasonably consistent with ~~reproduces~~ the AM3 forcing evolutions throughout the 20th Century ~~as compared to AM3~~. Preindustrial to present-day forcings for CO_2 and methane simulated by AM3 and MAGICC are similar to those given by IPCC (Myhre et al., 2013), (1.68 from CO2 emissions and 0.97 W m-2 from methane emissions in 2011 relative to 1750 levels), albeit there are important differences, including baseline years (1750 for IPCC and 1870 for AM3 and MAGICC in this study to match that from AM3) and time series of atmospheric concentrations (Myhre et al., 2013). While the same radiation expressions are used for IPCC and MAGICC for CO2 and methane atmospheric concentrations, the representation of tropospheric ozone chemistry and its radiation effects in MAGICC is extremely simplified due to hemispheric averages in a four-box atmosphere. For a short-lived climate forcer that is highly spatially variable, this is a vastly different treatment than that by the IPCC, which employs multi-model assessments for tropospheric ozone forcings. We find that our direct methane forcing in MAGICC in model year 2011 is 0.45 W m^{-2}, extremely close to the IPCC's forcing of 0.48 W m^{-2} from changes in methane concentrations alone (recall however different baselines) (Myhre et al., 2013). However, when methane interactions with other chemical species are accounted for, MAGICC estimates a forcing of 0.7 W m^{-2} attributed to changes in methane compared to the IPCC's value of 0.97 W m^{-2} (Myhre et al., 2013). ~~, and present-day forcings are consistent with the IPCC (2013) forcings attributed to CO_2 and methane emissions (1.68 and 0.97 W m^{-2} in 2011, respectively) (Myhre et al., 2013).~~

In MAGICC, methane's RF is consistently around half the value of that by CO_2. In AM3, methane's RF is much closer to that of CO_2 until the year 2000 and beyond where they diverge. ~~Before 1950, the difference between methane's RF in MAGICC vs. AM3 is consistent with internal variability, but after 1950, AM3's methane forcing exhibits a large increase not captured by MAGICC. AM3~~ While this ~~also shows a slight decrease in methane RF around the year 2000 through 2005,~~ divergence is consistent with global atmospheric methane concentrations ~~remaining flat~~levelling off for about a decade in the mid-1990s to ~~early~~ mid-2000s, before rapidly increasing from 2007 onwards (Fig. 1), further simulations are required (such as more ensemble members or adjustments to input conditions) in order to determine if the close methane and CO_2 RFs before 2000 are an artefact of unforced variability or a substantiated feature. Based on our analysis of unforced variability in AM3, it is quite possible that they are features of internal variability.

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Methane's role in radiative forcing can be divided into direct contributions via warming by methane as a greenhouse gas, and indirect contributions via production of other greenhouse gases (mainly tropospheric ozone) as it oxidizes to CO_2 in the atmosphere. Figure 4~~3~~ compares the direct and indirect methane forcings from MAGICC and AM3, calculated via Eqs. (3) and (4), respectively. The results from AM3 further highlight the role of unforced variability in complicating perceived responses to small forcing changes; the seemingly large swings in AM3 forcings deviate from that of MAGICC by around 0.25 W m^{-2} at most, which is within the realm of unforced variability (see Fig. 2).. ~~Each model attributes around 35-40% of methane's present-day total RF to indirect effects, and temporal patterns are consistent with each other~~ While correlation coefficients show consistency between MAGICC and AM3 (direct r^2 = 0.87; indirect r^2 = 0.7~~8~~6), the strong variability in AM3 makes comparisons of magnitude difficult. MAGICC attributes around 35% of methane's present-day total radiative forcing to indirect effects, similar to the IPCC's attribution of 34% (Myhre et al., 2013). AM3 shows magnitudes of indirect forcings in the present-day that are around 30-50% of the total methane forcing, depending on the year; this variation is due to unforced variability. ~~The larger methane forcing in AM3 post-1950 is apparent in both the direct and indirect forcings, although the 2000-2005 decrease in RF is dominated by the indirect component of the methane forcing (mostly tropospheric ozone). A time lag roughly on the order of methane's atmospheric lifetime (around 12 years) is present between the peaks and valleys of the AM3 direct and indirect methane forcings.~~

3.2 Global Surface Air Temperature Change

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To build confidence in the simulation of surface air temperature by both MAGICC and CM3, we compare the model results with 20th Century reconstructions of surface air temperature, of which several independent datasets are available. Figure 5~~4~~ shows the historical global-mean surface air temperature responses to changes in all-forcings in MAGICC and CM3 compared with NOAA and National Aeronautics and Space Administration (NASA) time series of global surface temperature anomalies ~~data~~, freely available online (https://www.ncdc.noaa.gov/cag/time-series/global and https://data.giss.nasa.gov/gistemp/). Following NOAA's methodology (NOAA, 2017), we compute the 20th Century average temperatures in MAGICC, CM3, and NASA, and calculate the annual temperature departures from this baseline.

The two ~~independent~~ observational datasets are perfectly correlated (r^2 = 1.00). While MAGICC and CM3 both have high correlations with NOAA and NASA data, MAGICC has much higher correlation coefficients (MAGICC r^2 = 0.92 (NOAA) and 0.93 (NASA); CM3 r^2 = 0.7~~6~~5 (NOAA) and 0.7~~5~~6 (NASA)), likely due to the absence of internal variability. Consistent with Fig. 3~~2~~, CM3 shows lower temperature responses post-1960 due to the strong effect of aerosols (Golaz et al. 2013). We note, however, that the 'lingering' temperature response in CM3 to major volcanic eruptions is an artefact of the 5-year running mean smoothing process; this is why CM3 temperature responses to volcanic eruptions persist longer than what is seen in the observational records and by MAGICC. This is not found, however, to considerably impact the correlation coefficients between the CM3 data and the NOAA/NASA data. Overall, the general temperature anomaly temporal patterns reveal that both models adequately reproduce surface air temperature, providing confidence in both climate models of differing complexity levels.

The global mean surface air temperature responses attributed to CO_2 and methane forcings are shown in Fig. 65, calculated via Eqs. (1) and (2), respectively. The correlations of the ensemble-means are extremely high (CO_2 r^2 = 0.98; methane r^2 = 0.92). Figure 65 also shows individual CM3 initial condition-driven ensemble members and the range of MAGICC responses from all 19 AOGCM calibrations; however, we do not include MAGICC's highest climate sensitivity physics-driven ensemble member as the responses were a clear outlier to the rest of the ~~ensemble~~ members.

We find that both CM3 and MAGICC attribute a nearly 1 ºC rise in temperature from 1860 to 2014 from rising CO_2 concentrations (CM3: 0.9 ºC; MAGICC: 0.9 ºC). For methane, CM3 suggests a rise of 0.5 ºC and MAGICC suggests a rise of 0.4 ºC, consistent with the larger methane forcing in CM3 (Fig. 32). It is important to note that cooling from aerosols mask some of the warming that we otherwise would be experiencing from CO_2 and methane, which is why the combined warming from CO_2 and methane is larger than today's observed warming.

~~There are t~~Two major features of the temperature response ~~features~~to methane in CM3, that are not present in MAGICC, further highlight the difficulty of extracting a small signal (and with a small ensemble) given the size of the unforced variability (Fig. 65): methane's forcing is considerably smaller than that of CO_2, making it difficult to extract a temperature response from the variability. The first ~~-~~feature is a global mean cooling response to methane forcings around 1900 to 1915, which is strongly apparent in two of the three initial condition-driven ensemble members. ~~, Interestingly, t~~This cooling response is ~~-~~not clearly reflected in the forcings of both the direct and indirect methane responses, and while total methane forcings in AM3 are slightly negative (at most -0.15 W m^{-2}) from 1895 to 1900, they are positive (around 0.2 W m^{-2} on average) from 1900 to 1915 ~~-~~(Figs. 3 and 42). The second feature is a strong warming signal in response to methane from 1980 to 1995, followed by cooling through 2000; while this is consistent with AM3 RFs (Fig. 32), ~~but~~ the feature is more pronounced in the temperature ~~signals~~response. Both of these features fall within the range of annual temperature swings due to unforced variability in CM3 (at most around 0.2 ºC for a five-year running mean). Therefore, we cannot conclude that they are robust responses to methane, but rather serve as a further example of why CCMs are difficult to employ for small individual forcings and the need for large ensembles.

~~Analyzing~~To dig into these features further, we analyse regional surface air temperature responses to CO_2 and methane isolated forcings (Fig. 76)~~, shows that the m~~Methane-induced cooling between 1900 and 1915 is mostly attributed to the Southern Hemisphere and especially over Southern Hemisphere oceans. This is likely due to the southern ocean polynya (Gordon and Comiso, 1988), which can be very strong in CM3, leading to very large unforced multidecadal time-scale variability over the southern ocean that propagates throughout the Southern Hemisphere (e.g., de Lavergne et al., 2014). On the other hand, the large methane warming in CM3 around 1990 is most prominent in the Northern Hemisphere, over both land and ocean.

When the global mean responses are parsed out by region (Fig. 76), the highest surface air temperature responses to methane and CO_2 are found over land in the Northern Hemisphere, with temperatures from CO_2 rising by well over 1 ºC from 1860 to 2014 in both models. There is high correlation between MAGICC and CM3 for all regions. We expect and find methane

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correlations between the two models to be slightly lower than CO_2 because methane has more complex chemical interactions in the atmosphere than CO_2 that introduce more degrees of freedom than CO_2, and are also potentially more simplified in MAGICC. We also find that correlations in the Southern Hemisphere are lower than in the Northern Hemisphere, especially for methane.

As seen and discussed earlier in Fig. 3 forcings, ~~An interesting feature present in the CM3 global mean and regional responses and not paralleled by MAGICC is that~~ there are several time periods ~~before 1950~~ when the methane temperature responses are comparable in magnitude to that by CO_2 in CM3 global mean and regional responses (Fig. 6~~5~~ and 7~~6~~). We see this for all initial condition-driven ensemble members, and it is consistent with AM3 RFs (Fig. 3~~2~~). In the ensemble mean, the comparable warming magnitudes between 1940 and 1950 are consistent with the rate of growth of CO_2 concentrations slowing down while methane concentrations consistently increase (Fig. 1).

Also discussed earlier and in ~~I~~in contrast to the CO_2 and methane concentration trends from 1940-1950, the methane concentration growth rate slows down in the 1990s while the CO_2 concentrations consistently increase (Fig. 1). This is reflected in the CM3 temperature trends in addition to forcings (Fig. 3) as a divergence in the magnitude of temperature responses between methane and CO_2 to where they stand in the present-day, with CO_2 yielding twice as much warming in 2014 as methane (Fig. 6~~5~~).

~~A major difference between CM3 and MAGICC is the role of unforced variability in CM3. Ensemble member means and running averages are employed to dampen out variability, but it still plays a large role in decadal forcing and temperature responses. CM3, in particular, has been shown to produce magnitudes of variability on the upper end of CMIP5 models (Brown et al., 2015). To isolate the role of unforced variability in CM3, we plot a control simulation with constant preindustrial (1860) external radiative forcings for 500 years (Fig. 7). Temperature responses from unforced internal dynamics in CM3 introduce decadal temperature swings of 0.5 °C on average.~~

4 Conclusions

The purpose of this study is to enhance confidence in a freely available and computationally efficient reduced complexity climate model, MAGICC, in the context of simulating temperature responses to methane and CO_2 atmospheric concentrations. Our analysis is motivated by the need to determine a quick and accessible, yet reliable, method for ~~analyzing~~analysing impacts of future changes in methane emissions on climate warming. Given that sophisticated coupled climate-chemistry models are generally inaccessible, ~~and/or~~ time-intensive, and employ high internal variability that obscures the response signal, ~~and thus unavailable~~they are generally unsuitable for analysis of methane mitigation strategies.~~,~~ ~~e~~Employing a model like MAGICC, rather than ~~relying on~~resorting to simple GWP metrics, would significantly enhance the accuracy of ~~the~~ mitigation assessments while still using basic infrastructure and ~~meeting quick turnaround times~~providing immediate guidance for decision making.

To determine MAGICC's reliability for methane analysis, we performed ~~four~~ several sets of experiments using MAGICC and CM3—all forcing with both time-varying natural and anthropogenic forcings but land-use held constant; simulations where CO_2 and methane concentrations are held constant at 1860 levels, respectively; and a simulation to isolate methane indirect effects resulting from its influence on ozone and water ~~vapor~~vapour (for MAGICC, we turned off methane chemistry; for CM3, we held methane radiative effects at 1860 levels). We also ran simulations using the atmosphere-only version of CM3, AM3, to calculate radiative forcings in response to the four sets of experiments. Finally, we ran control simulations for AM3 and CM3 to determine the role of unforced variability in influencing climate responses.

Both CM3 and MAGICC models ~~accurately~~ adequately reconstruct surface air temperature records from NOAA and NASA from 1860 through 2014, especially for 1950 onwards. For isolated forcings, overall temporal patterns were consistent between MAGICC ~~was able to adequately replicate~~and CM3 temperature responses to methane and CO_2, including for indirect effects via methane chemical reactions. Correlation coefficients were very high at 0.98 and 0.92 in the global mean for CO_2 and methane, respectively, with overall magnitudes consistent. We therefore conclude that MAGICC is able to reproduce the general isolated greenhouse gas forcing results (temporal patterns and magnitudes) of a more sophisticated coupled global climate model, providing confidence in the use of MAGICC for understanding the climate implications of methane mitigation analyses.

Further, we find that methane accounts for a considerable fraction of 20th Century and early 21st Century warming—roughly half that of CO_2's warming response. However, there are some ~~details captured by~~features present in CM3 results without parallels in MAGICC. ~~that suggest comparable warming contribution from both methane and CO_2 during the second half of the 20th Century. This is due to a larger direct and indirect methane forcing simulated by CM3 compared to MAGICC. CM3 also exhibits a range of~~ The features are, however, consistent in magnitude with forcing and temperature fluctuations due to unforced variability, and therefore are unable to be classified as robust responses~~, not predicted by MAGICC~~. ~~Whilst this acts as a hindrance to uncovering a forced signal, it also serves as a useful threshold for understanding the size of a forcing signal required for attribution.~~ A good example of this is that CM3 exhibits a cooling response to methane from 1900 to 1915 likely due to the formation of the southern ocean polynya leading to very large unforced multidecadal time-scale climate variability. This highlights how unforced variability present in sophisticated models can make it difficult to ascertain robust responses to small changes in multiple forcings individually, further justifying the use of a model such as MAGICC beyond pure accessibility. To overcome this challenge, a larger number of ensembles could be employed or simulations can be run with a quasi-chemistry-transport model (Deckert et al. 2011).

~~More research is clearly needed to explore and evaluate these regional climate responses to increases in individual greenhouse gases.~~

Overall, we find that MAGICC, a reduced complexity climate model, is able to satisfactorily match the global mean temperature response to increases in isolated greenhouses gases as simulated by the GFDL-CM3, a complex chemistry-climate model. Furthermore, we find that the prominent role of unforced variability in AM3 and CM3 makes it difficult to clearly

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assess climate responses to small forcing changes, ultimately supporting further use of models like MAGICC, that have little to no unforced variability, for analysing climate responses to future changes in methane emissions.

Code availability

The MAGICC v6 model (the executable file) is available for download at: http://www.magicc.org/download upon registration. The user manual can be accessed at: http://wiki.magicc.org/index.php?title=Manual_MAGICC6_Executable. Full model details along with nineteen sets of AOGCM-calibrated parameters used here for the physics-driven ensemble members are found in Meinshausen et al. (2011a). We update the default values of methane and tropospheric ozone radiative efficiency and methane atmospheric lifetime to values in Myhre et al. (2013).

The atmospheric model component (AM3) source code for GFDL CM3 is available here: https://www.gfdl.noaa.gov/am3-model/. The ocean model component (MOPM5) source code for GFDL CM3 is available here: https://www.gfdl.noaa.gov/mom-ocean-model/.

Data availability

Results from CM3/AM3 simulations and from the MAGICC model are available from Vaishali Naik (vaishali.naik@noaa.gov) and Ilissa Ocko (icko@edf.org), respectively, upon request.

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	Experiments	Abbreviation	MAGICC v6	GFDL CM3
Direct Simulations	All-Forcing	AllForc	X	X
	CO_2 concentrations held constant at 1860 levels	$CO_2$1860	X	X
	~~CH4~~ Methane concentrations held constant at 1860 levels	$CH_4$1860	X	X
	All-Forcing with ~~CH4~~ methane chemistry turned off	CH_4nochem	X	
	~~CH4~~ Methane concentrations held ~~constant~~ at 1860 levels with ~~CH4~~ methane chemistry turned off	$CH_4$1860nochem	X	
	~~CH4~~ Methane ~~held~~ concentrations held at 1860 for radiation ~~constant at 1860 levels for radiation only~~	$CH_4$1860chem$_{\text{norad}}$		X
	Methane concentrations held at 1860 for chemistry	$CH_4$1860chem		X
Derived Simulations	CO_2-only	AllForc – $CO_2$1860		
	CH_4-only	AllForc – $CH_4$1860		
	CH_4-direct	CH_4nochem – ~~AllForc~~		

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$CH_4$1860nochem	~~CH_4norad~~AllForc – $CH_4$1860rad	
CH_4-only – CH4-direct	AllForc – $CH_4$1860chem	
CH_4-indirect	~~CH_4norad – $CH_4$1860~~	

Table 1. Direct experiments performed by MAGICC and GFDL-CM3 models, as well as derived simulations. All-Forcing simulations include time-varying natural and anthropogenic forcings but land-use held constant. Each experiment is run for 19 physics-driven ensemble members for MAGICC and three initial condition-driven ensemble members for GFDL-CM3 over the period 1860 – 2014.

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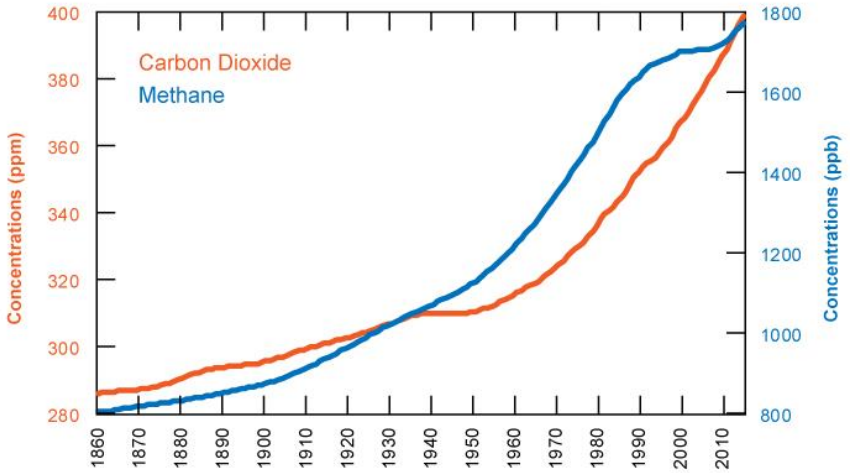
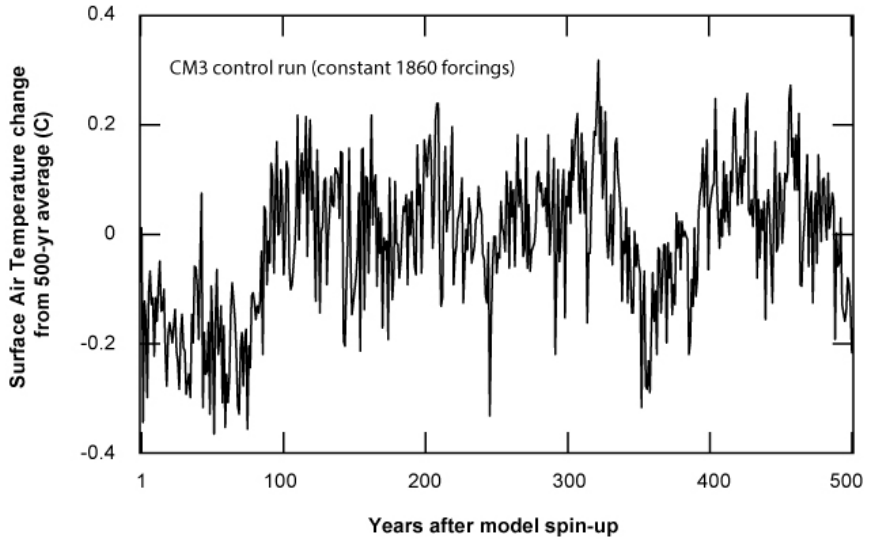


Figure 1. Atmospheric concentrations of carbon dioxide in parts per million (orange) and methane in parts per billion (blue) used in this study (Meinshausen et al. 2011b). Note that concentrations are prescribed for CM3 throughout this time period, but only prescribed for MAGICC through 2005, of which methane emissions inputs drive the model from 2006-2014. The resulting concentrations are plotted here.


CM3 control run (constant 1860 forcings)
Surface Air Temperature change from 500-yr average (C)
0.4
0.2
0
-0.2
-0.4
1
100
200
300
400
500
Years after model spin-up

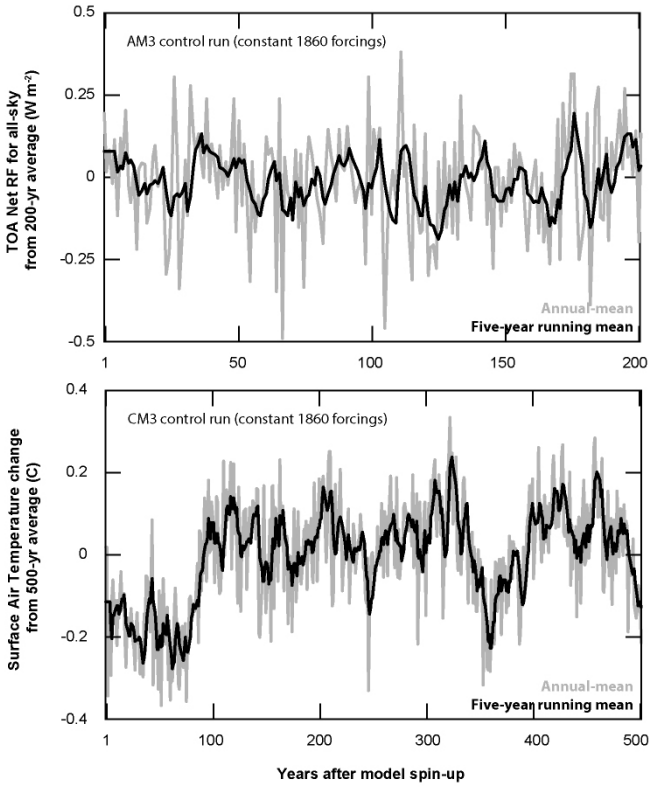


Figure 27. Control run simulations for AM3 and CM3 with preindustrial (1860) forcings held constant for 200 and 500 years post-spin-up, respectively. Top-of-atmosphere radiative forcing fluctuations for all-sky conditions in W m^{-2} introduced by unforced variability in AM3. Surface air temperature fluctuations in ºC introduced by unforced variability in CM3. ~~Preindustrial (1860) forcings held constant with model run for 500 years post- 3000 year spin-up.~~ Results shown for annual averages and five-year running means.

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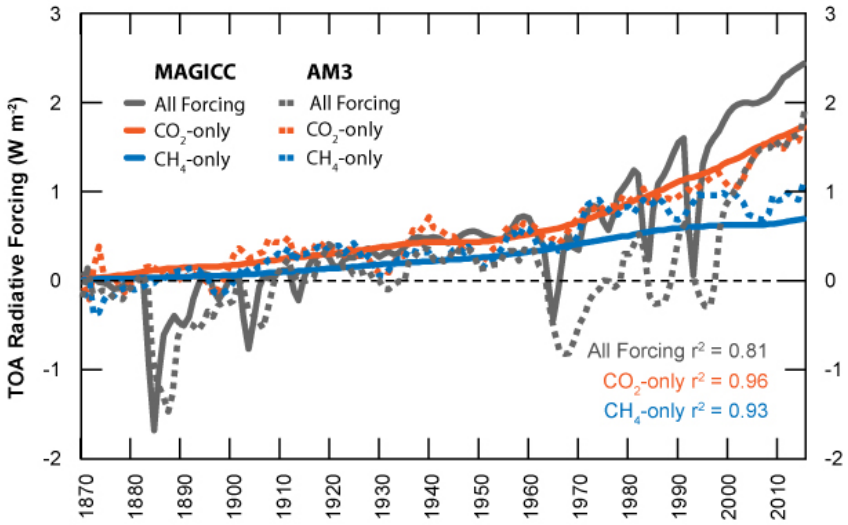

MAGICC
All Forcing
CO2-only
CH4-only
AM3
All Forcing
CO2-only
CH4-only
TOA Radiative Forcing (W m-2)
All Forcing r2 = 0.81
CO2-only r2 = 0.96
CH4-only r2 = 0.93
3
2
1
0
-1
-2
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010

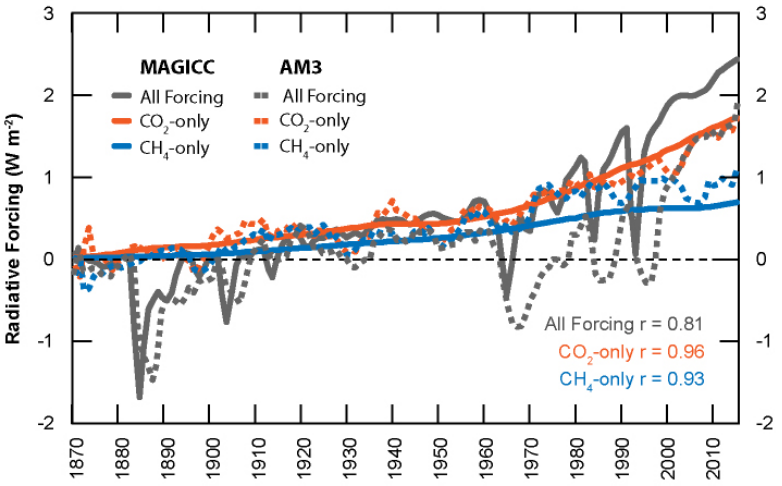
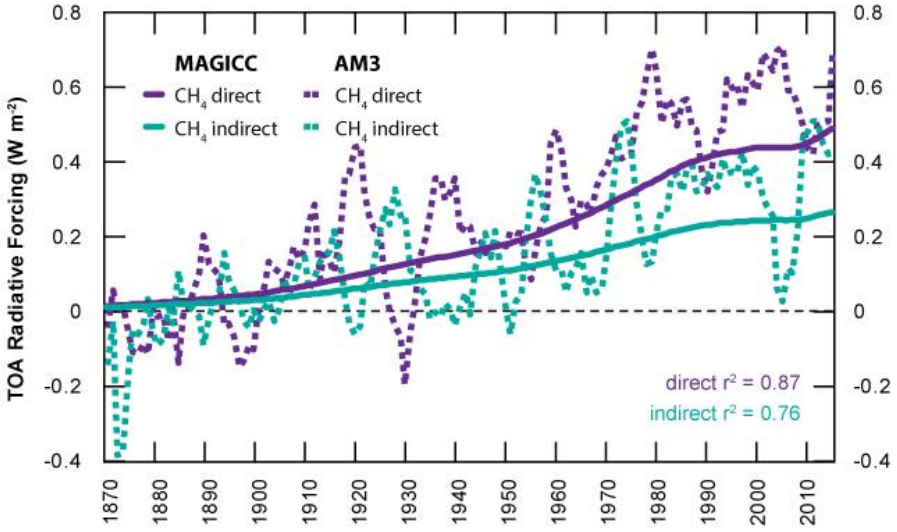


Figure 32. ~~Top-of-atmosphere r~~Radiative forcings (W m^{-2}) after stratospheric adjustment due to all forcing (grey), CO_2-only (orange), methane-only (blue), for both AM3 (dashed) and MAGICC (solid) model simulations. Methane forcing includes its direct as well as indirect effect from influences on chemistry. AM3 radiative forcings are ~~technically~~ 'effective' radiative forcings, and include tropospheric adjustments as well, and are calculated at the top-of-atmosphere (TOA). MAGICC radiative forcings are calculated at the tropopause. AM3 data are 5-year running means. Correlation coefficients between MAGICC and AM3 radiative forcings are shown inset.


TOA Radiative Forcing (W m-2)
MAGICC
CH4 direct
CH4 indirect
AM3
CH4 direct
CH4 indirect
direct r2 = 0.87
indirect r2 = 0.76
0.8
0.6
0.4
0.2
0
-0.2
-0.4
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010

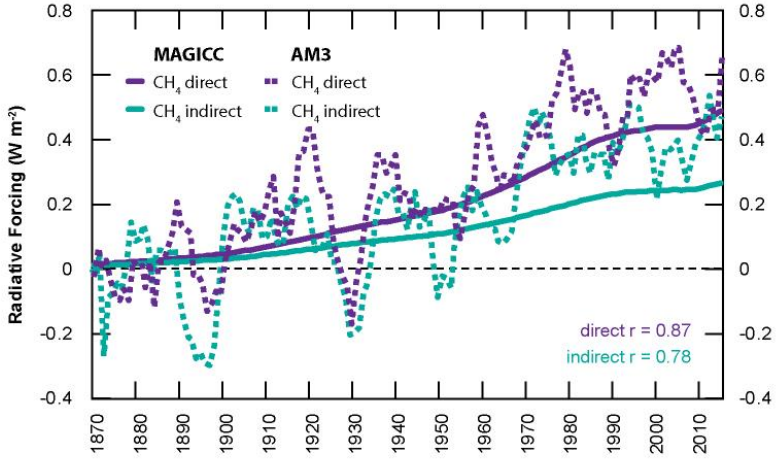

Radiative Forcing (W m-2)
MAGICC
CH4 direct
CH4 indirect
AM3
CH4 direct
CH4 indirect
direct r = 0.87
indirect r = 0.78
0.8
0.6
0.4
0.2
0
-0.2
-0.4
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010

Figure ~~3~~4. Direct (purple) and indirect (from methane's influence on ozone and water ~~vapor~~vapour, green) ~~top-of-atmosphere~~ radiative forcings (W m^{-2}) after stratospheric adjustment, for both AM3 (dashed) and MAGICC (solid) model simulations. AM3 radiative forcings are technically 'effective' radiative forcings, and include tropospheric adjustments as well, and are calculated at the top-of-atmosphere. MAGICC radiative forcings are calculated at the tropopause. AM3 data are 5-year running means. Correlation coefficient between MAGICC and AM3 forcings are also shown.

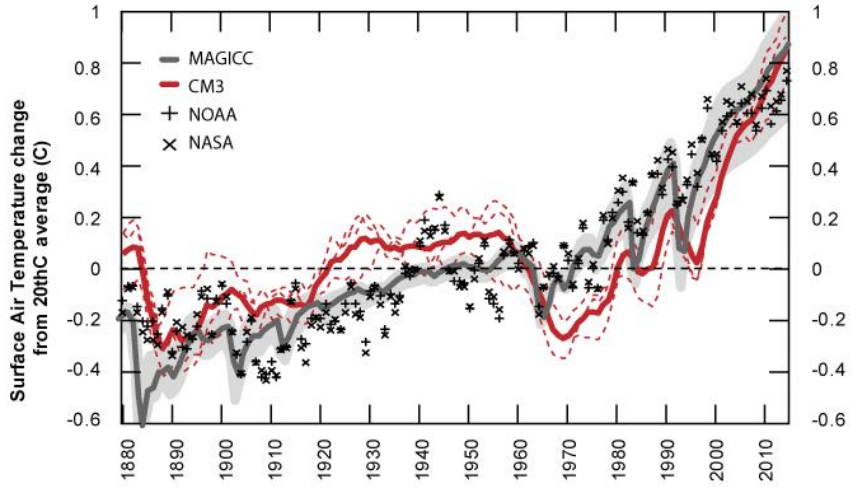
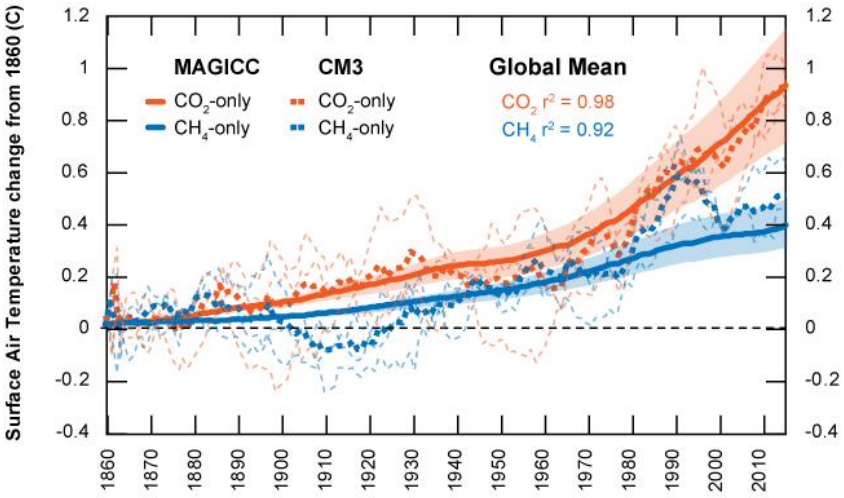


Figure ~~4~~5. All forcing global-mean surface air temperature responses in °C for CM3 (solid red line) and MAGICC (solid grey line) model simulations as compared to observations by NOAA (+) (https://data.giss.nasa.gov/gistemp/) and NASA (x) (https://www.ncdc.noaa.gov/cag/time-series/global). All annual temperature anomalies shown as change from 20th Century average for each dataset. Individual initial condition-driven ensemble members for CM3 runs shown in thin dashed red lines. Physics-driven ~~E~~ensemble-member range for MAGICC shown as shaded grey. CM3 data are 5-year running means.


Surface Air Temperature change from 1860 (C)
MAGICC
CO2-only
CH4-only
CM3
CO2-only
CH4-only
Global Mean
CO2 r2 = 0.98
CH4 r2 = 0.92
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010

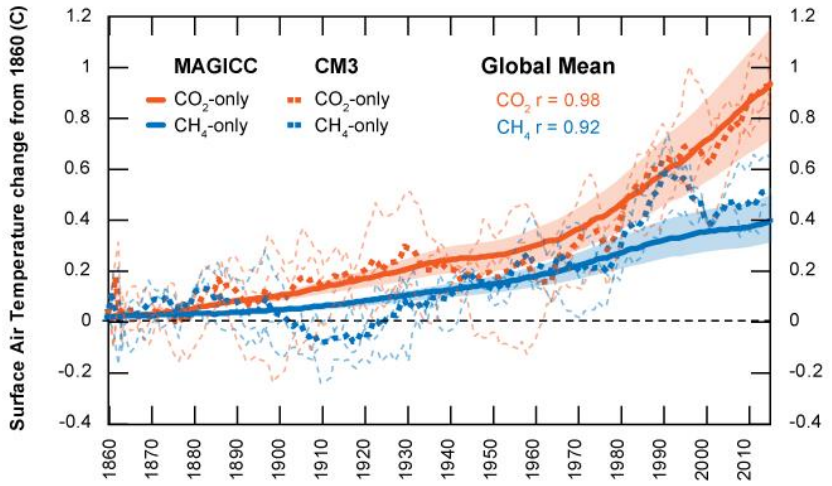
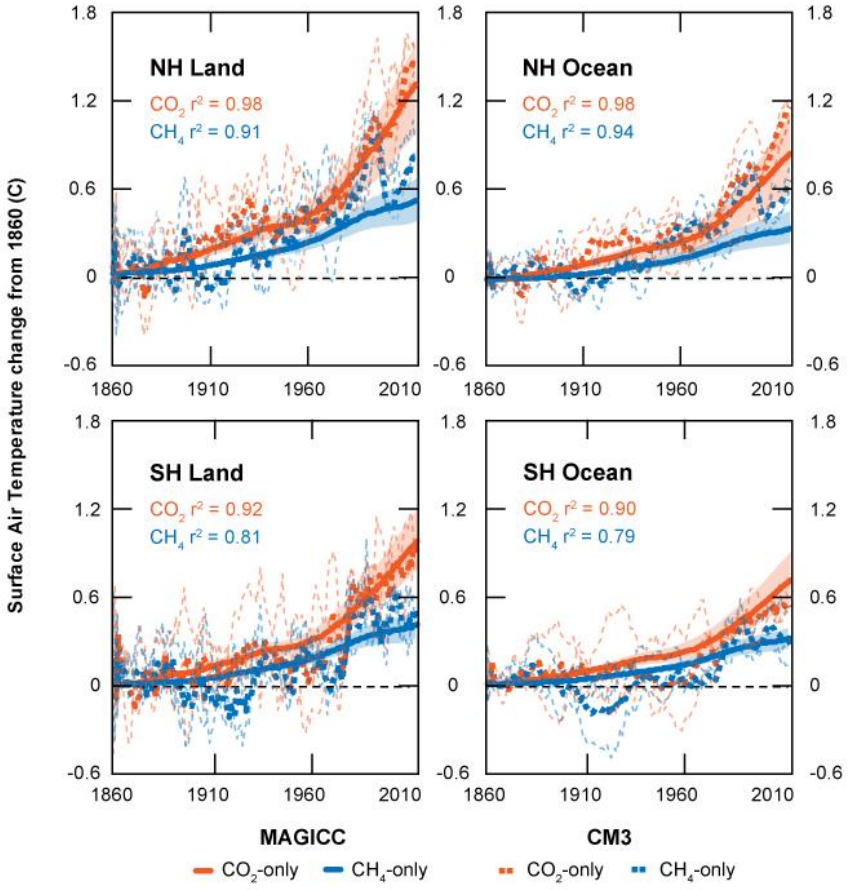


Figure 65. Global mean surface air temperature responses in °C for CM3 (dashed line) and MAGICC (solid line) model derived simulations – CO_2-only (orange) and methane-only (blue). Individual initial condition-driven ensemble members for CM3 runs shown in thin dashed lines. Range for MAGICC physics-driven ensemble- members shown in shaded ~~colors~~colours. CM3 data are 5-year running means. Correlation coefficient between MAGICC and CM3 temperature responses are also shown.


Surface Air Temperature change from 1860 (C)
NH Land
CO2 r2 = 0.98
CH4 r2 = 0.91
NH Ocean
CO2 r2 = 0.98
CH4 r2 = 0.94
SH Land
CO2 r2 = 0.92
CH4 r2 = 0.81
SH Ocean
CO2 r2 = 0.90
CH4 r2 = 0.79
1.8
1.2
0.6
0
-0.6
1860
1910
1960
2010
MAGICC
CM3
CO2-only
CH4-only
CO2-only
CH4-only

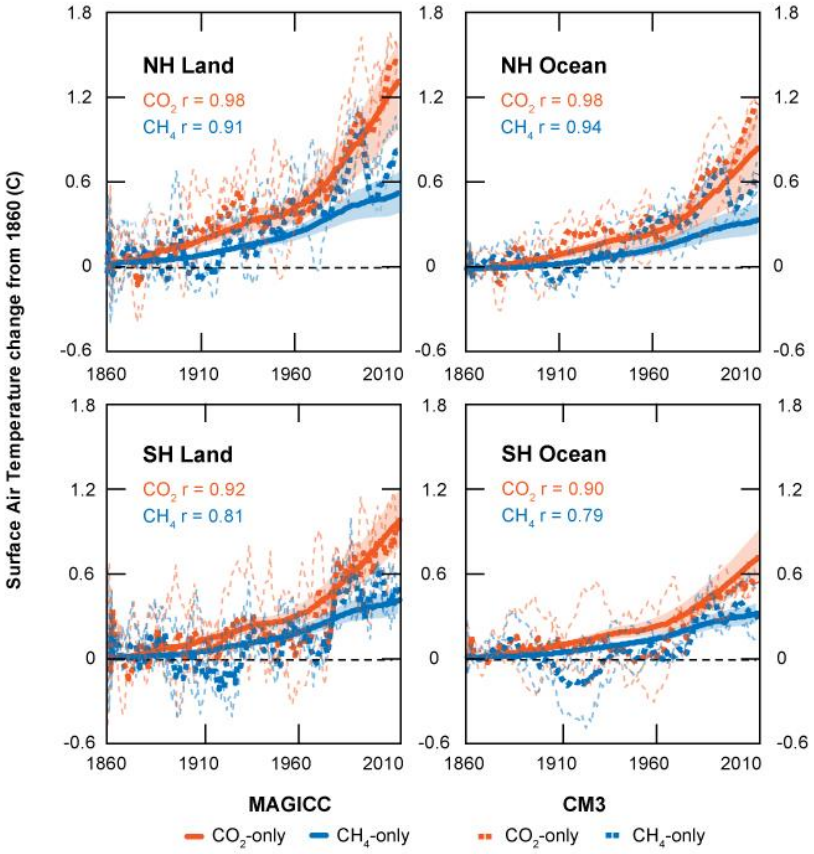
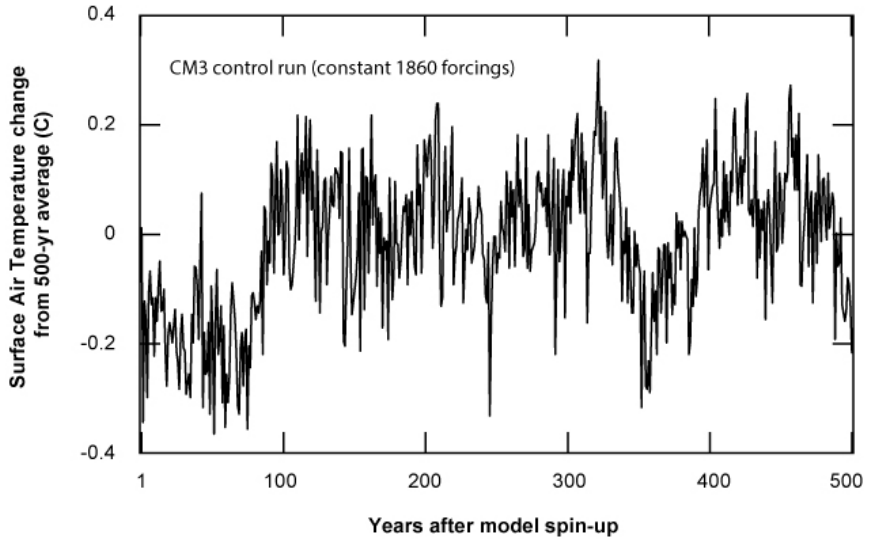


Figure 76. Regional surface air temperature responses in ºC for CM3 (dashed line) and MAGICC (solid line) model indirect simulations – CO_2-only (orange) and methane-only (blue). Individual initial condition-driven ensemble members for CM3 runs shown in thin dashed lines. Range for MAGICC physics-driven ensemble members shown in shaded ~~color~~colours. CM3 data are 5-year running means. Correlation coefficient between MAGICC and CM3 temperature responses are also shown.



~~Figure 7. Surface air temperature fluctuations in °C introduced by unforced variability in CM3. Preindustrial (1860) forcings held constant with model run for 500 years post- 3000 year spin-up.~~

Rapid and reliable assessment of methane impacts on climate

Ilissa B. Ocko[1], Vaishali Naik[2] and David Paynter[2]

[1]Environmental Defense Fund, Washington DC, 20009, USA
[2]NOAA Geophysical Fluid Dynamics Laboratory, Princeton, 08540, USA

Correspondence to: Ilissa B. Ocko (iocko@edf.org)

Abstract. It is clear that the most effective way to limit global temperature rise and associated impacts is to reduce human emissions of greenhouse gases, including methane. However, quantification of the climate benefits of mitigation options are complicated by the contrast in the timescales at which short-lived climate pollutants, such as methane, persist in the atmosphere as compared to carbon dioxide. Whereas simple metrics fail to capture the differential impacts across all timescales, sophisticated climate models that can address these temporal dynamics are often inaccessible, time-intensive, require special infrastructure, and include high unforced interannual variability that makes it difficult to analyse small changes in forcings. Reduced-complexity climate models offer an ideal compromise in that they provide quick, reliable insights into climate responses to relatively small changes in forcings of different climate pollutants, due to the absence of strong internal variability, using basic knowledge and limited computational infrastructure. In this paper, we build on previous evaluations of the freely-available and easy-to-run reduced-complexity climate model MAGICC by comparing temperature responses to historical methane emissions to those from a more complex coupled global chemistry-climate model, GFDL CM3. While we find that the overall forcings and temperature responses are comparable between the two models, the prominent role of unforced variability in CM3 demonstrates how sophisticated models are potentially inappropriate tools for small forcing scenarios. On the other hand, we find that MAGICC can easily and rapidly provide robust data on climate responses to changes in methane emissions with clear signals unfettered by variability. We are therefore able to build confidence in using MAGICC for purposes of understanding the climate implications of methane mitigation.

1 Introduction

Reduced-complexity climate models offer an ideal framework for evaluating greenhouse gas mitigation options if they can accessibly and rapidly reproduce the results of the more complex global chemistry-climate models (CCMs) that include more advanced and comprehensive treatments of chemistry and physics (Meinshausen et al., 2011a). However, there is a critical need to build confidence in the ability of reduced-complexity models to simulate temperature responses to individual greenhouse gases rather than just the suite of climate pollutants, because greenhouse gases have vastly different radiative properties and atmospheric lifetimes (Myhre et al., 2013; Fiore et al., 2015); it is important to confirm that individual species

are represented appropriately if reduced-complexity models are to serve as an effective tool for assessing climate benefits of mitigation actions. This is especially central for the analysis of methane (CH_4) mitigation actions, of which the climate policy community has been increasingly focused on (e.g., Shindell et al., 2012; Collins et al., 2018). Therefore, this paper builds on previous evaluations by comparing forcing and temperature responses to historical methane and carbon dioxide (CO_2) concentrations from a widely-used reduced-complexity climate model, with that from a state-of-the-art coupled global chemistry-climate model. While it is difficult to compare climate responses of simple models with that of complex ones because of the presence of unforced variability in the latter, we ultimately seek to determine if general temporal patterns and magnitudes are consistent enough to justify the use of a reduced-complexity climate model as a reliable tool for rapid assessment of methane mitigation measures.

Climate change impacts have now been observed on every continent and in every ocean (Stocker et al., 2013). If we want to reduce near- and long-term anthropogenically caused warming, then we need to reduce emissions of several climate pollutants. While limiting long-term climate warming requires drastically reducing CO_2 emissions, reducing emissions of short-lived climate pollutants (SLCPs)—specifically, methane and black carbon (BC)—has been identified as one of the most effective ways to reduce near-term warming (e.g., Ramanathan and Xu, 2010; Shindell et al., 2012; Rogelj et al., 2013; Shoemaker et al., 2013). Methane emissions in particular account for a quarter of the excess energy trapped by human emissions, and today's global anthropogenic methane emissions will have a larger impact on near-term warming than today's global fossil fuel CO_2 emissions (based on forcing data provided in Myhre et al., 2013 and references therein; methane emissions provided in EPA, 2012; CO_2 emissions provided in IEA, 2015; and radiative efficiency estimates of methane provided in Etminan et al., 2016). Sustained methane emissions will also impact long-term warming (Allen et al., 2016). Furthermore, reducing methane emissions has air quality, health, and food security co-benefits (Shindell et al., 2012; West et al., 2013; Zhang et al., 2016; Melvin et al., 2016).

Most methane mitigation measures are assessed as a comparison to carbon dioxide warming impacts; almost all policy analyses rely on the simple metric Global Warming Potential (GWP) because of its simplicity and ease of use (Ocko et al., 2017). However, GWP is limited in its ability to quantify climate effects because it relies on the integrated impact of a pulse of emissions over a specified time horizon. Because methane and CO_2 have vastly different atmospheric lifetimes, their respective climate impacts occur over different timescales. Due to the inherent selection of a single time horizon, GWP is incapable of capturing these important temporal distinctions (e.g., Solomon et al. 2010; Alvarez et al., 2012) unless two time horizons that represent near- and long-term impacts are reported simultaneously (Ocko et al., 2017).

Assessment of SLCP climate impacts over different timescales can be performed using comprehensive global chemistry-climate models (CCMs), however, a full assessment of various SLCP scenarios using sophisticated CCMs is computationally intensive and time-consuming, and forcing perturbations from slight changes in individual species are often too small for the response signal to be detected among the high unforced internal climate variability present in CCMs (e.g., Ocko et al., 2014).

Determining robust climate responses to small-forcing scenarios using CCMs therefore requires a large number of ensemble simulations (Deser et al., 2012). Given that many institutions do not have access to CCMs nor the technical capacity or expertise to run these models, they must rely on partnerships with modelling centres that are often focused on model development. These characteristics of CCMs reinforces the use of the simple GWP metric for assessments of climate pollutant mitigation measures.

While detailed assessment of regional climate responses can only be provided by complex CCMs, reduced-complexity climate models offer a useful alternative for global changes in major climate characteristics that is far more advanced than GWP but avoids the need for the tremendous amount of computational resources required to perform CCM simulations (and especially with enough ensemble members to average out unforced variability). These simpler models can rapidly analyse global average climate responses because they are easily accessible and quick to run, thereby providing immediate scientific guidance for mitigation assessments. Further, because they do not include unforced internal variability, they provide clear responses to small forcing scenarios without any noise. .

There are several models that have been developed that fall within this intermediate complexity class—more advanced than simple metrics but far less sophisticated than CCMs. They range from simplified expressions (e.g., Shine et al. 2005) to more complex chemistry and physics but computations of only a few climate indicators averaged over large spatial domains (e.g., Meinshausen et al. 2011a; Hartin et al. 2014). One of the latter is the freely available Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC), initially developed in the late 1980s (Wigley and Rapper, 1987, 1992) and routinely updated since (e.g., Meinshausen et al., 2011a). While not meant to replace atmosphere-ocean global climate models (AOGCMs) and carbon cycle models, MAGICC is a complementary, computationally-inexpensive tool that is capable of efficiently analysing basic climate responses (such as radiative forcing, surface air temperature, and ocean heat uptake) to a suite of emission scenarios. Confidence in MAGICC results comes from a comprehensive effort to match several AOGCMs and carbon cycle models (Meinshausen et al., 2008, 2011a). Evaluations show that MAGICC closely reproduces temperature responses to aggregated forcings from the sophisticated Coupled Model Intercomparison Project CMIP3 atmosphere-ocean and C4MIP carbon cycle models (Meinshausen et al., 2011c).

While not the only model of its class, the reduced complexity model MAGICC is an especially great resource for mitigation analysis because of its widespread use in international climate reports, and the ability of the user to modify future emissions of every radiatively active species. Therefore, when numerous scenarios exist and need to be evaluated for decision-making, a rapid tool like MAGICC can provide rapid insight into the climate impacts of various options. However, to build confidence in MAGICC's evaluation of greenhouse gas mitigation strategies, we need to adequately assess its ability to reproduce climate responses to individual greenhouse gases beyond the aggregated forcings. Here, we analyse the capability of MAGICC in simulating climate responses to historical increases (1860-2014) in methane and CO_2 by comparing the results with that from a state-of-the-art coupled chemistry-climate model, the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL) CM3 model, which has been shown to adequately reproduce historical

temperature trends (Golaz et al. 2013, Griffies et al., 2011; Donner et al., 2011; Winton et al., 2012; John et al., 2012; Levy et al., 2013). While it is difficult to compare simpler models with sophisticated ones for scenarios with small forcings – due to high interannual variability built into the latter – it is nevertheless important to do so because of the more advanced and comprehensive chemistry and physics in the more complex models.

We compare the response of the two models to assess similarities and differences, seeking to determine (i) if the forcings/temperature response comparable; (ii) if the complexity of the CCM provides any benefits over the simple model; and (iii) does the lack of variability in the simple model provide any advantages over the CCM when looking at small forcing amounts. Our goal is to build confidence in the simulation of the climate response to methane in order to justify future use of MAGICC to assess the climate impact of methane emissions mitigation scenarios. In this analysis, we add to previous evaluations by showing a high correlation between CM3's and MAGICC's radiative forcing and surface air temperature responses to changes in either CO_2 or methane in isolation, despite large unforced variability in CM3, thereby strengthening confidence in MAGICC's simulation of climate responses to individual greenhouse gases with vastly different radiative properties and lifetimes.

2 Models and Simulations

2.1 MAGICC model description

We use MAGICC v.6 version developed in 2011 (http://www.magicc.org/download). MAGICC represents the complex coupled carbon-cycle climate system as a hemispherically averaged upwelling-diffusion ocean coupled to an atmosphere layer and a globally averaged carbon cycle model. The atmosphere has four boxes (one over land and one over ocean for each hemisphere) and is coupled to the mixed layer of the ocean hemispheres. The default number of ocean layers in each hemisphere is 50 including the mixed layer (though users can select the number of levels), and heat exchange is driven by vertical diffusion and advection. The terrestrial carbon cycle model is a globally integrated box model with one living plant box and two dead biomass boxes (one for detritus and one for organic matter in soils). The terrestrial carbon cycle does not feedback into carbon dioxide concentrations in the atmosphere. The sea-to-air carbon flux is determined by the partial pressure differential for carbon dioxide between the atmosphere and surface layer of the ocean.

From 1765–2005, the MAGICC v.6 radiative forcing is driven by global-mean concentrations of greenhouse gases (carbon dioxide, methane, nitrous oxide, ozone-depleting substances and their replacements); prescribed regional direct aerosol radiative forcings (sulphate, black and organic carbon, sea salt, mineral dust); land-use, volcanic, and solar radiative forcings; prescribed black carbon on snow radiative forcings; emissions of tropospheric ozone precursors (carbon monoxide, nitrogen oxides, non-methane volatile organic carbon); and indirect (first and second) aerosol forcings calculated from prescribed regional aerosol optical depths (parameterizations described in detail in Meinshausen et al. (2011a)). For 2006 to 2014, the

model is driven by emissions of gases and aerosols taken from the Representative Concentration Pathway (RCP8.5) scenario to capture a business-as-usual trajectory. Climate responses (such as surface air temperature) are provided as global annual averages and also across four spatial boxes (over land and ocean and by hemisphere).

Historical greenhouse gas concentrations are from Meinshausen et al. (2011b); prescribed aerosol forcings and land-use historical forcings are from the National Aeronautics and Space Administration (NASA) GISS model (http://data.giss.nasa.gov/); solar irradiance is provided by Lean et al. (2010); and historical emissions of ozone precursors are from Lamarque et al. (2010). Present-day and future (2005–2100) forcings are driven by emissions of gases and aerosols, and are taken from the Representative Concentration Pathway (RCP8.5) scenario to capture a business-as-usual trajectory, though we restrict our analysis here to climate responses from 1860–2014. Carbon dioxide radiative forcings are calculated using a standard simplified expression (Shine et al. 1990 with updated scaling parameter from Myhre et al. 1998). Methane radiative forcings are calculated using a radiative efficiency parameter in conjunction with standard simplified expressions from Myhre et al. (1998), and accounts for overlap between methane and nitrous oxide absorption bands.

For the most recent version of MAGICC, seven key climate parameters were calibrated to match 19 AOGCMs used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report AR4 (see Meinshausen et al., 2011a). The parameters include: equilibrium climate sensitivity, land-ocean warming ratio at equilibrium, vertical diffusivity in the ocean, sensitivity of feedback factors to radiative forcing change, sensitivity of vertical diffusivity at mixed layer boundary to global-mean surface temperatures (i.e., thermal stratification), land-ocean heat exchange coefficient, and an amplification factor for the ocean to land heat exchange. The MAGICC parameter set that best reproduces surface air temperatures and heat uptake of each AOGCM is determined via an optimization routine with 1000 iterations to find the combination that minimizes the squared differences between low-pass filtered time series. The effective climate sensitivities in MAGICC v.6 vary over time due to spatially non-homogenous varying feedbacks, until they reach the equilibrium climate sensitivity. The equilibrium climate sensitivity input into MAGICC depends on which AOGCM calibration is used; they range from 1.9 to 5.73 °C across all 19 models, with a mean (median) of 2.88 °C (2.59 °C). Multi-model-ensembles are generated by running each simulation for all 19 AOGCM calibrations, which we refer to as "physics-driven ensemble members." The user of the downloaded MAGICC model can select which parameters to use for each simulation.

While the MAGICC model is particularly well-calibrated to more sophisticated models, the realism of MAGICC results relies on the realism of GCMs, which have their own sets of limits and uncertainties. Further limitations of MAGICC include incomplete knowledge of forcing patterns, unknown responses outside of the calibrated range, limited set of climate responses evaluated (such as temperature and heat uptake but not precipitation), reliance on a high level of parametrization (such as cloud feedbacks tuned to match those of more sophisticated GCMs), and possible errors in the data used for calibration. However, despite these limitations, MAGICC has been shown to reasonably reproduce climate responses to all-forcing scenarios (Meinshausen et al., 2011a).

2.2 CM3 model description

We employ the GFDL global coupled atmosphere-ocean-chemistry model (GFDL-CM3; Donner et al., 2011; Griffies et al., 2011) to assess the climate response to historical changes in methane and CO_2. CM3 uses a finite-volume dynamical core on a cubed-sphere horizontal grid composed of six faces; each face includes 48×48 grid cells. The size of the grid cells range from 163 km at the corners to 231 km near the face centres. In the vertical, the model domain extends from the surface up to 0.01 hPa (86 km) with 48 vertical hybrid sigma pressure levels. The model simulates tropospheric and stratospheric chemistry interactively over the full vertical domain, with simulated ozone and aerosols influencing radiation calculations (Naik et al., 2013; Austin et al., 2013). Ensemble members for CM3 are generated by employing different sets of stochastically-selected initial conditions (discussed in more detail in Sect. 2.3.), which we refer herein as "initial condition-driven ensemble members." The equilibrium climate sensitivity of CM3 is 4.8 K (Paynter et al., 2018), which is higher than that of MAGICC.

Global mean concentrations of well-mixed greenhouse gases (WMGHGs), including carbon dioxide, nitrous oxide, methane, and ozone-depleting substances (ODSs) are specified for radiation calculations for the historical period (1860-2005) from Meinshausen et al. (2011b) and for the period 2006 to 2014 following the Representative Concentration Pathway (RCP8.5) scenario. Within the chemistry module, global mean concentrations of methane are prescribed at the surface as the lower boundary condition and are allowed to undergo chemistry everywhere else in the model domain. Radiation calculations do not see the full three-dimensional methane field (simulated in the chemistry module) and only employ the global-mean concentrations, however, changes in ozone and water vapour are seen by the radiation. Further, CM3 CO_2 concentrations do not get altered by reactions that occur in the model.

CM3 is forced with emissions of short-lived species including ozone precursors, and aerosols and their precursors, volcanic aerosols, solar radiation, and land-use change as described in detail by Donner et al. (2011) and Naik et al. (2013). Anthropogenic emissions, including from biomass burning and ships, for the time period 1860–2005 are from the dataset of Lamarque et al. (2010) developed in support of the Couple Model Intercomparison Project Phase 5 (CMIP5). For years 2006–2014, anthropogenic emissions follow the RCP8.5 scenario. Natural emissions of all precursor species, except isoprene, are included as described by Naik et al. (2013). Biogenic isoprene emissions are calculated interactively, as described by Lin et al. (2012), based on the Model of Emissions of Gases and Aerosols in Nature (MEGAN) (Guenther et al., 2012). 'Explosive' volcanic eruptions are imposed via a time series of volcanic optical properties rather than from direct injection of sulphur into the stratosphere (Stenchikov et al., 2006; Donner et al., 2011).

Shortwave and longwave radiation algorithms in CM3 are described in Freidenreich and Ramaswamy (1999) and Schwarzkopf and Ramaswamy (1999), respectively, with some modification to enhance computational efficiency (GAMDT 2004). The shortwave algorithm includes 18 bands in the solar spectrum, and the longwave algorithm includes eight bands. Shortwave radiation parameterizations account for absorption by water vapour, carbon dioxide, ozone, molecular oxygen; molecular scattering; and absorption and scattering by aerosols and clouds. The longwave radiation parameterizations account for

absorption and emission by water vapour, carbon dioxide, ozone, nitrous oxide, methane, halocarbons (CFC-11, CFC-12, CFC-13 and HCFC-22), aerosols, and clouds. Aerosols included are sulphate, carbonaceous (black and organic carbon), dust, and sea salt.

CM3 includes explicit representation of both the direct and indirect aerosol effects on radiation. For the calculation of the direct effect of aerosols on radiation, physical and optical properties of sulphate, black carbon, organic carbon, sea salt, and dust are considered in the model (Donner et al., 2011). Sulphate and black carbon are assumed to be internally mixed while all other aerosols are assumed to be externally mixed for radiation calculations. To account for the indirect effect of aerosols via aerosol-water cloud interactions, the model treats water soluble aerosols, including sea salt, and organic aerosols as cloud-condensation nuclei (CCN) allowing a physically based parameterization of CCN activation (Ming et al., 2006). The model does not consider the reduction in surface albedo caused by the deposition of black carbon on snow-covered surfaces.

2.3 Simulations

Three historical simulations are run for both MAGICC and GFDL CM3 to derive climate responses to isolated CO_2 and methane concentrations, respectively. MAGICC was run from 1750 to 2100 by default, and CM3 was run from 1860 to 2014. As shown in Table 1, the direct runs for both models include an all-forcing simulation with all forcings varying with time except land-use; a simulation with CO_2 concentrations held at 1860 levels; and a simulation with methane concentrations held at 1860 levels. Subtracting temperature responses of the two latter runs from the former yield CO_2-only and methane-only climate responses, respectively (see Eqs. (1) and (2). The same equations hold for the forcings as well.

$$\Delta T_{CO2} = T_{AllForc} - T_{CO21860}\,, \tag{1}$$

$$\Delta T_{CH4} = T_{AllForc} - T_{CH41860}\,, \tag{2}$$

For MAGICC, each simulation is run for all 19 AOGCM-calibrated configurations; each 350-year integration took approximately one second to run on a modern PC with a three GHz CPU processing speed. We use default MAGICC gas and aerosol properties, but update methane and tropospheric ozone radiative efficiencies and methane atmospheric lifetime to IPCC Fifth Assessment Report (AR5) values (Myhre et al., 2013; Stevenson et al., 2013) to reflect the latest science. (Note that the updated atmospheric lifetime only impacts the model from 2006-2014 as it is driven by emissions and not concentrations during this period.) However, we do not include newer estimates of methane radiative efficiency that account for shortwave absorption in addition to longwave absorption (Etminan et al., 2016) to be consistent with the CM3 model that only includes longwave effects. Including the shortwave component increases methane's radiative efficiency by over 20%. Further, we specifically do not tune MAGICC model climate and forcing properties to match that of CM3 because we are assessing how a "standard version" of the reduced-complexity climate model compares with CM3; the goal is not to match MAGICC to CM3

but to assess whether a downloaded version of MAGICC broadly behaves similarly to CM3. However, two of MAGICC's physics-driven ensemble members are derived from two predecessors of CM3: CM2.0 and CM2.1 (Delworth et al., 2006).

The set-up of GFDL-CM3 simulations conducted here was similar to that adopted for simulations performed in support of the CMIP5, except we obtained initial conditions from a longer preindustrial control (3000 years). Three-member initial condition-driven ensembles of transient CM3 simulations were performed with each ensemble member initialized stochastically at different points in the preindustrial control simulation. Each 155-year integration of CM3 took about 15 days to complete on the NOAA's Remotely Deployed High Performance Computing System (RDHPCS) machine known as "Gaea" running on 464 processors. While three ensemble members is relatively small, we are limited by computational resources and studies have shown that forced changes in air temperature, as opposed to changes in atmospheric circulation and precipitation, can be detected with fewer ensemble members (Deser et al., 2012).

To compute CM3 radiative forcings for CO_2 and methane (direct and indirect) that are closest to the definition used by MAGICC (the forcing at the tropopause after stratospheric temperature adjustment), we performed simulations with the atmosphere-only version of CM3—AM3. The model configuration of AM3 was exactly the same as CM3 except AM3 model integrations over the period 1870 to 2014 were performed with observed sea-surface temperature and sea-ice cover (Rayner et al., 2003), and therefore do not include an ensemble driven by different initial conditions. Through the additional AM3 simulations, we were able to diagnose transient effective radiative forcing (ERF) (the change in net radiation balance at the top-of-atmosphere (TOA) following a perturbation to the climate system taking into account any rapid adjustments (Myhre et al., 2013)) due to CO_2 and methane. Transient ERF calculated in this way follow the proposed protocol for the AerChemMIP (Collins et al., 2016).

To separate the effect of methane due to its influence on ozone and water vapour (indirect effects) from its effect on radiation (direct effect), we ran two more simulations for MAGICC with methane chemistry turned off (an all-forcing run and methane held at 1860 levels run with methane chemistry turned off for both). Equation (3) shows how the direct methane forcings were calculated for MAGICC; subtraction between methane-only forcings and the direct forcings yielded the indirect responses to methane. We also ran two more simulations for AM3/CM3 with methane radiation calculations or chemistry held constant beyond 1860, respectively. Equations (4) and (5), respectively, show how the direct and indirect methane forcings were calculated in AM3.While we only show forcing calculations here via AM3 simulations with fixed sea surface temperatures, we also ran the simulations for the fully coupled CM3 model.

$$\Delta F_{CH4,direct\ (MAGICC)} = F_{CH4nochem} - F_{CH41860nochem}\ , \quad (3)$$

$$\Delta F_{CH4,direct\ (AM3)} = F_{AllForc} - F_{CH4rad1860}\ , \quad (4)$$

$$\Delta F_{CH4,indirect\ (AM3)} = F_{AllForc} - F_{CH4chem1860}\ , \quad (5)$$

The global mean historical concentrations of CO_2 and methane used by the models to calculate radiative forcings and therefore temperature changes are shown in Fig. 1. (Note that concentrations are prescribed for MAGICC only through 2005, and then emissions inputs drive the model thereafter; however, the resulting concentrations from these emissions are consistent with that input into CM3.) Results for both models are presented as an average of the individual ensemble members (initial condition-driven ensemble members for CM3 and physics-driven ensemble members for MAGICC). Surface air temperatures are taken to be 2 meters above the surface. For both models, we calculate temperature changes as the difference between temperatures in year *t* compared to that in 1860.

A key difference between AM3/CM3 and MAGICC is that the full GCM has internally generated unforced variability. This occurs both when the model is coupled (CM3) and run with prescribed sea surface temperatures and sea ice (AM3). The variability can be dampened by applying a smoothing to the annual time-series. However, too long of a smoothing period removes much of the decadal level forcing that we hope to uncover in this study. Therefore, we employ a five-year smoothing average to AM3/CM3 results to filter out some of the internal variability. Additionally, to better quantify and isolate the role of unforced variability in theAM3/CM3, we run control experiments of each with fixed forcing. For CM3 we ran a 500 year control simulation with all radiative forcing held constant at 1860 level. For AM3 we ran a shorter 200 year control run, with all radiative forcing held fixed at 1860 with annually repeating monthly averaged sea surface temperatures and sea ice characteristics taken from 30 years of the CM3 control run.

3 Results and Discussion

Here we analyse AM3/CM3's and MAGICC's radiative forcing and surface air temperature responses to changes in either CO_2 or methane in isolation.

Given that an important difference between AM3/CM3 and MAGICC results is the role of unforced variability in AM3/CM3, we first analyse the magnitudes of unforced variability in both AM3 and CM3. Although initial condition-driven ensemble member means and/or running averages are employed to dampen out some of the variability in AM3/CM3, it still plays a large role in forcing and temperature responses. CM3, in particular, has been shown to produce magnitudes of variability on the upper end of CMIP5 models (Brown et al., 2015).

The results of the control simulations with constant preindustrial (1860) external radiative forcings are shown in Fig. 2. In the case of AM3 unforced radiative forcings at the top-of-atmosphere for all-sky conditions range from -0.18 to 0.21 W m^{-2} with a standard deviation of 0.07 W m^{-2} for a five-year running mean. We find the maximum swing between two consecutive five-year means to be 0.35 W m^{-2}. Sources of unforced variability in AM3 include a mixture of land snow/ice cover variability and just year-to-year variability in the weather; soil moisture may also play a role. For CM3, unforced internal dynamics yield temperature responses ranging from -0.27 to 0.24 °C for five-year running means with a standard deviation of 0.1 °C. We find

the maximum swing between two consecutive five-year means to be 0.2 °C. The variability is driven by interactions among the ocean-atmosphere-land systems. While unforced variability is a key component to modelling the climate system, it can mask or amplify responses to external forcings over short timescales (e.g., Brown et al., 2017). This makes it difficult to clearly assess responses to small external forcings, and provides further motivation for using simpler models like MAGICC for analysis of small forcing scenarios.

3.1 Radiative Forcing

Figure 3 shows the global-mean radiative forcings (RF) in response to the all-forcing scenario as well as forcings attributed to isolated CO_2 and methane concentrations, respectively. Note that AM3 forcings are taken as top-of-atmosphere and include rapid adjustments in the troposphere in addition to the stratosphere, and therefore are considered an effective RF, while MAGICC derived RF is calculated at the tropopause and only considers stratospheric temperature adjustment. MAGICC methane and CO_2 isolated forcings are much smoother than that of AM3 because of the lack of unforced variability in MAGICC. Some unexpected features in AM3 forcings (such as negative forcings in the earlier years despite increasing atmospheric concentrations) are likely due to unforced variability. Using the MAGICC forcings as a benchmark for a signal due to forced changes only, we find that nearly all of the deviations of AM3 fall within the range of internal variability as derived from the control simulation: 0.35 W m^{-2}. However, despite the slightly different forcing definitions and the unforced variability in AM3, all results are strongly correlated between AM3 and MAGICC (All-forcing r = 0.81, CO_2-only r = 0.96, CH4-only r = 0.93).

In the present-day (model year 2014), AM3 and MAGICC yield an all-forcing RF of 2.0 and 2.5 W m^{-2}, respectively; note that land use is held constant in this analysis. This is consistent with the IPCC (2013) values that show an all-forcing effective RF of 2.3 W m^{-2} in 2011 (Myhre et al., 2013). The magnitudes for the CM3 and MAGICC all-forcing radiative forcings are offset after 1960 (-1 W m^{-2} in 1960). This is due to AM3's strong aerosol indirect forcing (Golaz et al., 2010) beginning around this time when aerosol emissions in the mid-latitudes increased rapidly (Lamarque et al., 2010).

Isolating CO_2 and methane's contribution to overall forcings (Fig. 3), MAGICC is reasonably consistent with the AM3 forcing evolutions throughout the 20th Century. Preindustrial to present-day forcings for CO_2 and methane simulated by AM3 and MAGICC are similar to those given by IPCC (Myhre et al., 2013), (1.68 from CO2 emissions and 0.97 W m-2 from methane emissions in 2011 relative to 1750 levels), albeit there are important differences, including baseline years (1750 for IPCC and 1870 for AM3 and MAGICC in this study to match that from AM3) and time series of atmospheric concentrations (Myhre et al., 2013). While the same radiation expressions are used for IPCC and MAGICC for CO2 and methane atmospheric concentrations, the representation of tropospheric ozone chemistry and its radiation effects in MAGICC is extremely simplified due to hemispheric averages in a four-box atmosphere. For a short-lived climate forcer that is highly spatially variable, this is a vastly different treatment than that by the IPCC, which employs multi-model assessments for tropospheric ozone forcings. We find that our direct methane forcing in MAGICC in model year 2011 is 0.45 W m^{-2}, extremely close to the IPCC's forcing

of 0.48 W m^{-2} from changes in methane concentrations alone (recall however different baselines) (Myhre et al., 2013). However, when methane interactions with other chemical species are accounted for, MAGICC estimates a forcing of 0.7 W m^{-2} attributed to changes in methane compared to the IPCC's value of 0.97 W m^{-2} (Myhre et al., 2013).

In MAGICC, methane's RF is consistently around half the value of that by CO_2. In AM3, methane's RF is much closer to that of CO_2 until the year 2000 and beyond where they diverge. While this divergence is consistent with global atmospheric methane concentrations levelling off for about a decade in the mid-1990s to mid-2000s, before rapidly increasing from 2007 onwards (Fig. 1), further simulations are required (such as more ensemble members or adjustments to input conditions) in order to determine if the close methane and CO_2 RFs before 2000 are an artefact of unforced variability or a substantiated feature. Based on our analysis of unforced variability in AM3, it is quite possible that they are features of internal variability.

Methane's role in radiative forcing can be divided into direct contributions via warming by methane as a greenhouse gas, and indirect contributions via production of other greenhouse gases (mainly tropospheric ozone) as it oxidizes to CO_2 in the atmosphere. Figure 4 compares the direct and indirect methane forcings from MAGICC and AM3, calculated via Eqs. (3) and (4), respectively. The results from AM3 further highlight the role of unforced variability in complicating perceived responses to small forcing changes; the seemingly large swings in AM3 forcings deviate from that of MAGICC by around 0.25 W m^{-2} at most, which is within the realm of unforced variability (see Fig. 2).. While correlation coefficients show consistency between MAGICC and AM3 (direct r = 0.87; indirect r = 0.78), the strong variability in AM3 makes comparisons of magnitude difficult. MAGICC attributes around 35% of methane's present-day total radiative forcing to indirect effects, similar to the IPCC's attribution of 34% (Myhre et al., 2013). AM3 shows magnitudes of indirect forcings in the present-day that are around 30-50% of the total methane forcing, depending on the year; this variation is due to unforced variability.

3.2 Global Surface Air Temperature Change

To build confidence in the simulation of surface air temperature by both MAGICC and CM3, we compare the model results with 20th Century reconstructions of surface air temperature, of which several independent datasets are available. Figure 5 shows the historical global-mean surface air temperature responses to changes in all-forcings in MAGICC and CM3 compared with NOAA and National Aeronautics and Space Administration (NASA) time series of global surface temperature anomalies, freely available online (https://www.ncdc.noaa.gov/cag/time-series/global and https://data.giss.nasa.gov/gistemp/). Following NOAA's methodology (NOAA, 2017), we compute the 20th Century average temperatures in MAGICC, CM3, and NASA, and calculate the annual temperature departures from this baseline.

The two observational datasets are perfectly correlated (r = 1.00). While MAGICC and CM3 both have high correlations with NOAA and NASA data, MAGICC has much higher correlation coefficients (MAGICC r = 0.92 (NOAA) and 0.93 (NASA); CM3 r = 0.76 (NOAA) and 0.75 (NASA)), likely due to the absence of internal variability. Consistent with Fig. 3, CM3 shows lower temperature responses post-1960 due to the strong effect of aerosols (Golaz et al. 2013). We note, however, that the 'lingering' temperature response in CM3 to major volcanic eruptions is an artefact of the 5-year running mean smoothing

process; this is why CM3 temperature responses to volcanic eruptions persist longer than what is seen in the observational records and by MAGICC. This is not found, however, to considerably impact the correlation coefficients between the CM3 data and the NOAA/NASA data. Overall, the general temperature anomaly temporal patterns reveal that both models adequately reproduce surface air temperature, providing confidence in both climate models of differing complexity levels.

The global mean surface air temperature responses attributed to CO_2 and methane forcings are shown in Fig. 6, calculated via Eqs. (1) and (2), respectively. The correlations of the ensemble-means are extremely high (CO_2 r = 0.98; methane r = 0.92). Figure 6 also shows individual CM3 initial condition-driven ensemble members and the range of MAGICC responses from all 19 AOGCM calibrations; however, we do not include MAGICC's highest climate sensitivity physics-driven ensemble member as the responses were a clear outlier to the rest of the members.

We find that both CM3 and MAGICC attribute a nearly 1 ºC rise in temperature from 1860 to 2014 from rising CO_2 concentrations (CM3: 0.9 ºC; MAGICC: 0.9 ºC). For methane, CM3 suggests a rise of 0.5 ºC and MAGICC suggests a rise of 0.4 ºC, consistent with the larger methane forcing in CM3 (Fig. 3). It is important to note that cooling from aerosols mask some of the warming that we otherwise would be experiencing from CO_2 and methane, which is why the combined warming from CO_2 and methane is larger than today's observed warming.

Two major features of the temperature response to methane in CM3, that are not present in MAGICC, further highlight the difficulty of extracting a small signal (and with a small ensemble) given the size of the unforced variability (Fig. 6); methane's forcing is considerably smaller than that of CO_2, making it difficult to extract a temperature response from the variability. The first feature is a global mean cooling response to methane forcings around 1900 to 1915, which is strongly apparent in two of the three initial condition-driven ensemble members. This cooling response is not clearly reflected in the forcings of both the direct and indirect methane responses, and while total methane forcings in AM3 are slightly negative (at most -0.15 W m^{-2}) from 1895 to 1900, they are positive (around 0.2 W m^{-2} on average) from 1900 to 1915 (Figs. 3 and 4). The second feature is a strong warming signal in response to methane from 1980 to 1995, followed by cooling through 2000; while this is consistent with AM3 RFs (Fig. 3), the feature is more pronounced in the temperature response. Both of these features fall within the range of annual temperature swings due to unforced variability in CM3 (at most around 0.2 ºC for a five-year running mean). Therefore, we cannot conclude that they are robust responses to methane, but rather serve as a further example of why CCMs are difficult to employ for small individual forcings and the need for large ensembles.

To dig into these features further, we analyse regional surface air temperature responses to CO_2 and methane isolated forcings (Fig. 7). Methane-induced cooling between 1900 and 1915 is mostly attributed to the Southern Hemisphere and especially over Southern Hemisphere oceans. This is likely due to the southern ocean polynya (Gordon and Comiso, 1988), which can be very strong in CM3, leading to very large unforced multidecadal time-scale variability over the southern ocean that propagates throughout the Southern Hemisphere (e.g., de Lavergne et al., 2014). On the other hand, the large methane warming in CM3 around 1990 is most prominent in the Northern Hemisphere, over both land and ocean.

When the global mean responses are parsed out by region (Fig. 7), the highest surface air temperature responses to methane and CO_2 are found over land in the Northern Hemisphere, with temperatures from CO_2 rising by well over 1 ºC from 1860 to 2014 in both models. There is high correlation between MAGICC and CM3 for all regions. We expect and find methane correlations between the two models to be slightly lower than CO_2 because methane has more complex chemical interactions in the atmosphere than CO_2 that introduce more degrees of freedom than CO_2, and are also potentially more simplified in MAGICC. We also find that correlations in the Southern Hemisphere are lower than in the Northern Hemisphere, especially for methane.

As seen and discussed earlier in Fig. 3 forcings, there are several time periods when the methane temperature responses are comparable in magnitude to that by CO_2 in CM3 global mean and regional responses (Fig. 6 and 7). We see this for all initial condition-driven ensemble members, and it is consistent with AM3 RFs (Fig. 3). In the ensemble mean, the comparable warming magnitudes between 1940 and 1950 are consistent with the rate of growth of CO_2 concentrations slowing down while methane concentrations consistently increase (Fig. 1).

Also discussed earlier and in contrast to the CO_2 and methane concentration trends from 1940-1950, the methane concentration growth rate slows down in the 1990s while the CO_2 concentrations consistently increase (Fig. 1). This is reflected in the CM3 temperature trends in addition to forcings (Fig. 3) as a divergence in the magnitude of temperature responses between methane and CO_2 to where they stand in the present-day, with CO_2 yielding twice as much warming in 2014 as methane (Fig. 6).

4 Conclusions

The purpose of this study is to enhance confidence in a freely available and computationally efficient reduced complexity climate model, MAGICC, in the context of simulating temperature responses to methane and CO_2 atmospheric concentrations. Our analysis is motivated by the need to determine a quick and accessible, yet reliable, method for analysing impacts of future changes in methane emissions on climate warming. Given that sophisticated coupled climate-chemistry models are generally inaccessible, time-intensive, and employ high internal variability that obscures the response signal, they are generally unsuitable for analysis of methane mitigation strategies. Employing a model like MAGICC, rather than resorting to simple GWP metrics, would significantly enhance the accuracy of mitigation assessments while still using basic infrastructure and providing immediate guidance for decision making.

To determine MAGICC's reliability for methane analysis, we performed several sets of experiments using MAGICC and CM3—all forcing with both time-varying natural and anthropogenic forcings but land-use held constant; simulations where CO_2 and methane concentrations are held constant at 1860 levels, respectively; and a simulation to isolate methane indirect effects resulting from its influence on ozone and water vapour (for MAGICC, we turned off methane chemistry; for CM3, we held methane radiative effects at 1860 levels). We also ran simulations using the atmosphere-only version of CM3, AM3, to

calculate radiative forcings in response to the four sets of experiments. Finally, we ran control simulations for AM3 and CM3 to determine the role of unforced variability in influencing climate responses.

Both CM3 and MAGICC models adequately reconstruct surface air temperature records from NOAA and NASA from 1860 through 2014, especially for 1950 onwards. For isolated forcings, overall temporal patterns were consistent between MAGICC and CM3 temperature responses to methane and CO_2, including for indirect effects via methane chemical reactions. Correlation coefficients were very high at 0.98 and 0.92 in the global mean for CO_2 and methane, respectively, with overall magnitudes consistent. We therefore conclude that MAGICC is able to reproduce the general isolated greenhouse gas forcing results (temporal patterns and magnitudes) of a more sophisticated coupled global climate model, providing confidence in the use of MAGICC for understanding the climate implications of methane mitigation analyses.

Further, we find that methane accounts for a considerable fraction of 20th Century and early 21st Century warming—roughly half that of CO_2's warming response. However, there are some features present in CM3 results without parallels in MAGICC. The features are, however, consistent in magnitude with forcing and temperature fluctuations due to unforced variability, and therefore are unable to be classified as robust responses. A good example of this is that CM3 exhibits a cooling response to methane from 1900 to 1915 likely due to the formation of the southern ocean polynya leading to very large unforced multidecadal time-scale climate variability. This highlights how unforced variability present in sophisticated models can make it difficult to ascertain robust responses to small changes in multiple forcings individually, further justifying the use of a model such as MAGICC beyond pure accessibility. To overcome this challenge, a larger number of ensembles could be employed or simulations can be run with a quasi-chemistry-transport model (Deckert et al. 2011).

Overall, we find that MAGICC, a reduced complexity climate model, is able to satisfactorily match the global mean temperature response to increases in isolated greenhouses gases as simulated by the GFDL-CM3, a complex chemistry-climate model. Furthermore, we find that the prominent role of unforced variability in AM3 and CM3 makes it difficult to clearly assess climate responses to small forcing changes, ultimately supporting further use of models like MAGICC, that have little to no unforced variability, for analysing climate responses to future changes in methane emissions.

Code availability

The MAGICC v6 model (the executable file) is available for download at: http://www.magicc.org/download upon registration. The user manual can be accessed at: http://wiki.magicc.org/index.php?title=Manual_MAGICC6_Executable. Full model details along with nineteen sets of AOGCM-calibrated parameters used here for the physics-driven ensemble members are found in Meinshausen et al. (2011a). We update the default values of methane and tropospheric ozone radiative efficiency and methane atmospheric lifetime to values in Myhre et al. (2013).

The atmospheric model component (AM3) source code for GFDL CM3 is available here: https://www.gfdl.noaa.gov/am3-model/. The ocean model component (MOPM5) source code for GFDL CM3 is available here: https://www.gfdl.noaa.gov/mom-ocean-model/.

Data availability

Results from CM3/AM3 simulations and from the MAGICC model are available from Vaishali Naik (vaishali.naik@noaa.gov) and Ilissa Ocko (icko@edf.org), respectively, upon request.

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	Experiments	Abbreviation	MAGICC v6	GFDL CM3
Direct Simulations	All-Forcing	AllForc	X	X
	CO_2 concentrations held constant at 1860 levels	$CO_2$1860	X	X
	Methane concentrations held constant at 1860 levels	$CH_4$1860	X	X
	All-Forcing with methane chemistry turned off	CH_4nochem	X	
	Methane concentrations held at 1860 levels with methane chemistry turned off	$CH_4$1860nochem	X	
	Methane concentrations held at 1860 for radiation	$CH_4$1860chem		X
	Methane concentrations held at 1860 for chemistry	$CH_4$1860chem		X
Derived Simulations	CO_2-only		AllForc – $CO_2$1860	
	CH_4-only		AllForc – $CH_4$1860	
	CH_4-direct		CH_4nochem – $CH_4$1860nochem	AllForc – $CH_4$1860rad
	CH_4-indirect		CH_4-only – CH4-direct	AllForc – $CH_4$1860chem

Table 1. Direct experiments performed by MAGICC and GFDL-CM3 models, as well as derived simulations. All-Forcing simulations include time-varying natural and anthropogenic forcings but land-use held constant. Each experiment is run for 19 physics-driven ensemble members for MAGICC and three initial condition-driven ensemble members for GFDL-CM3 over the period 1860 – 2014.

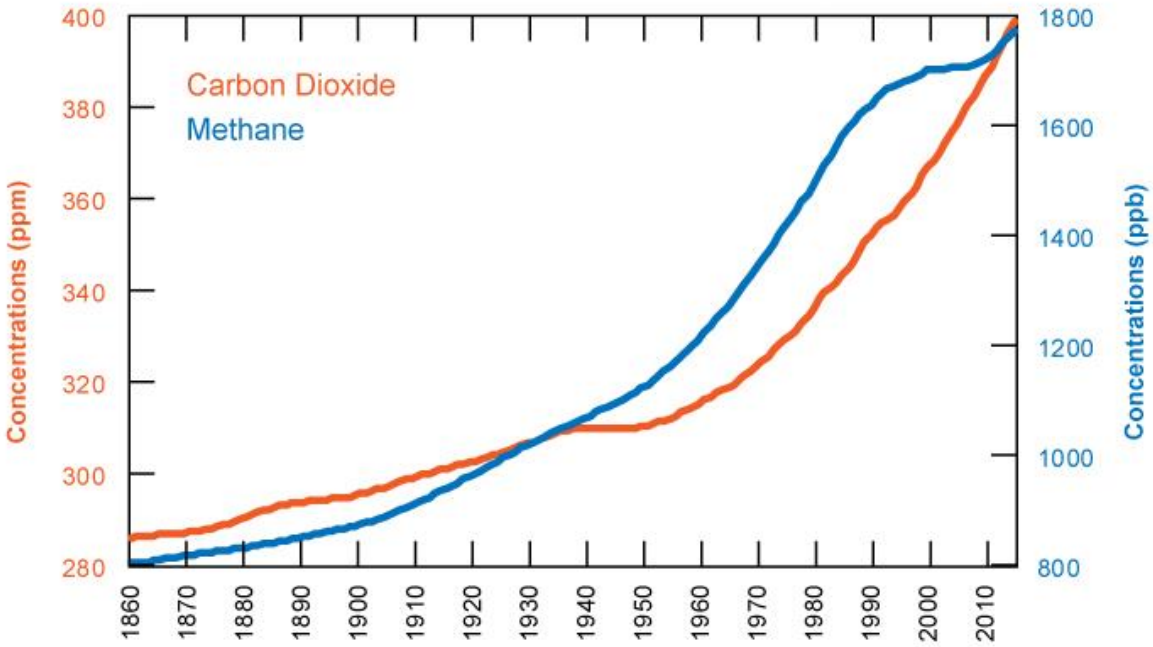

Figure 1. Atmospheric concentrations of carbon dioxide in parts per million (orange) and methane in parts per billion (blue) used in this study (Meinshausen et al. 2011b). Note that concentrations are prescribed for CM3 throughout this time period, but only prescribed for MAGICC through 2005, of which methane emissions inputs drive the model from 2006-2014. The resulting concentrations are plotted here.

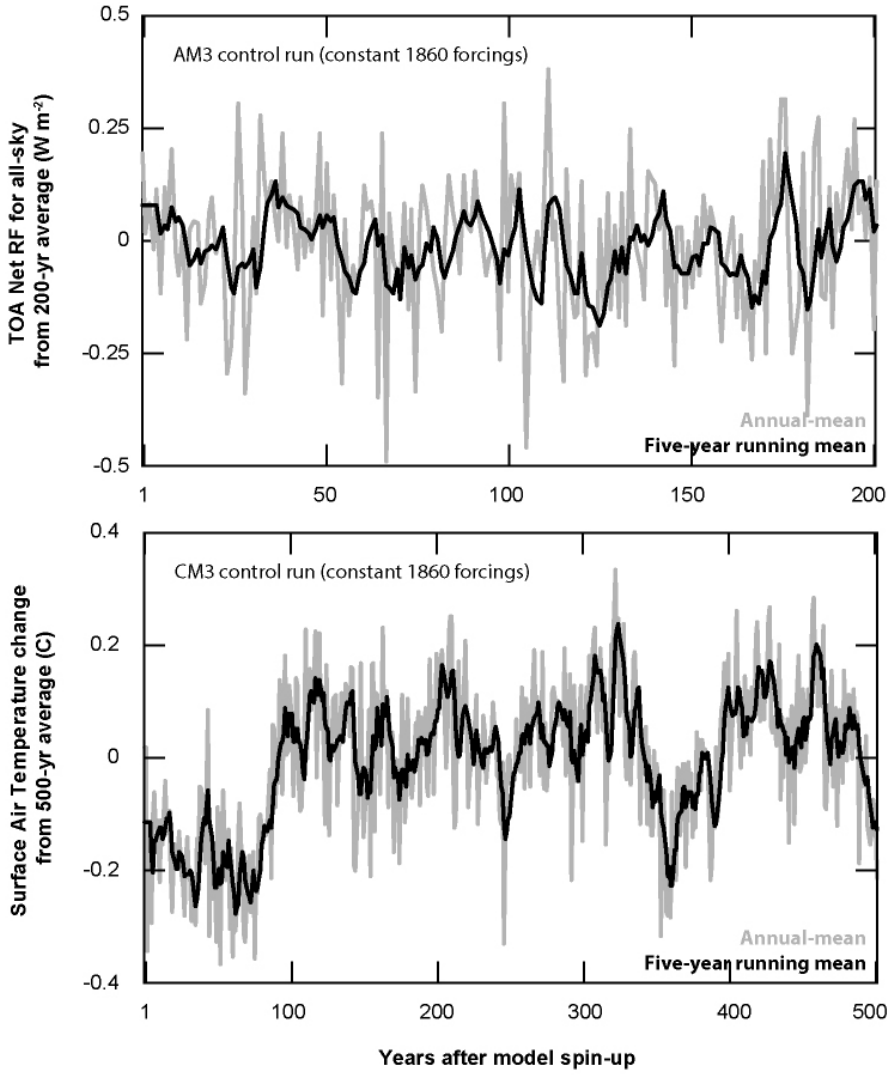

Figure 2. Control run simulations for AM3 and CM3 with preindustrial (1860) forcings held constant for 200 and 500 years post-spin-up, respectively. Top-of-atmosphere radiative forcing fluctuations for all-sky conditions in W m^{-2} introduced by unforced variability in AM3. Surface air temperature fluctuations in ºC introduced by unforced variability in CM3. Results shown for annual averages and five-year running means.

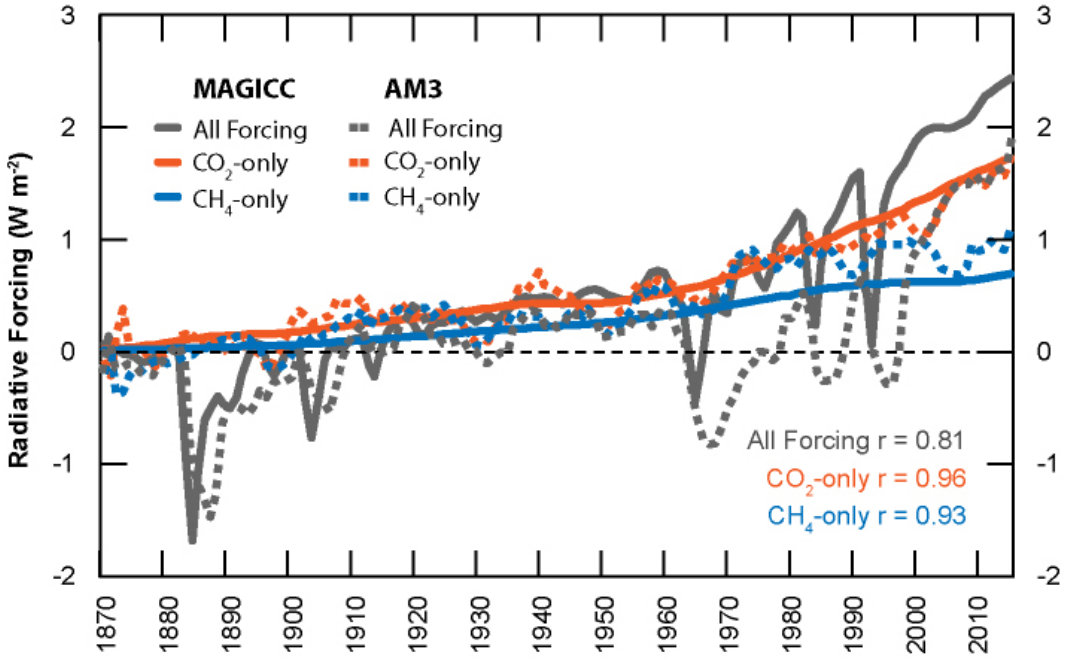

Figure 3. Radiative forcings (W m^{-2}) after stratospheric adjustment due to all forcing (grey), CO_2-only (orange), methane-only (blue), for both AM3 (dashed) and MAGICC (solid) model simulations. Methane forcing includes its direct as well as indirect effect from influences on chemistry. AM3 radiative forcings are 'effective' radiative forcings, and include tropospheric adjustments as well, and are calculated at the top-of-atmosphere (TOA). MAGICC radiative forcings are calculated at the tropopause. AM3 data are 5-year running means. Correlation coefficients between MAGICC and AM3 radiative forcings are shown inset.

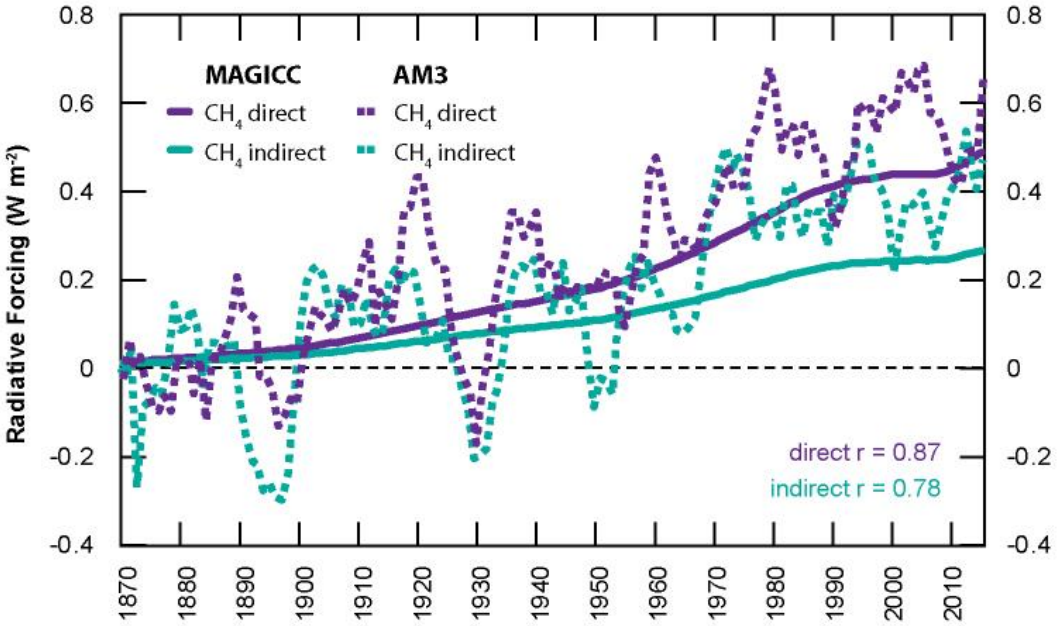

Figure 4. Direct (purple) and indirect (from methane's influence on ozone and water vapour, green) radiative forcings (W m^{-2}) after stratospheric adjustment, for both AM3 (dashed) and MAGICC (solid) model simulations. AM3 radiative forcings are technically 'effective' radiative forcings, and include tropospheric adjustments as well, and are calculated at the top-of-atmosphere. MAGICC radiative forcings are calculated at the tropopause. AM3 data are 5-year running means. Correlation coefficient between MAGICC and AM3 forcings are also shown.

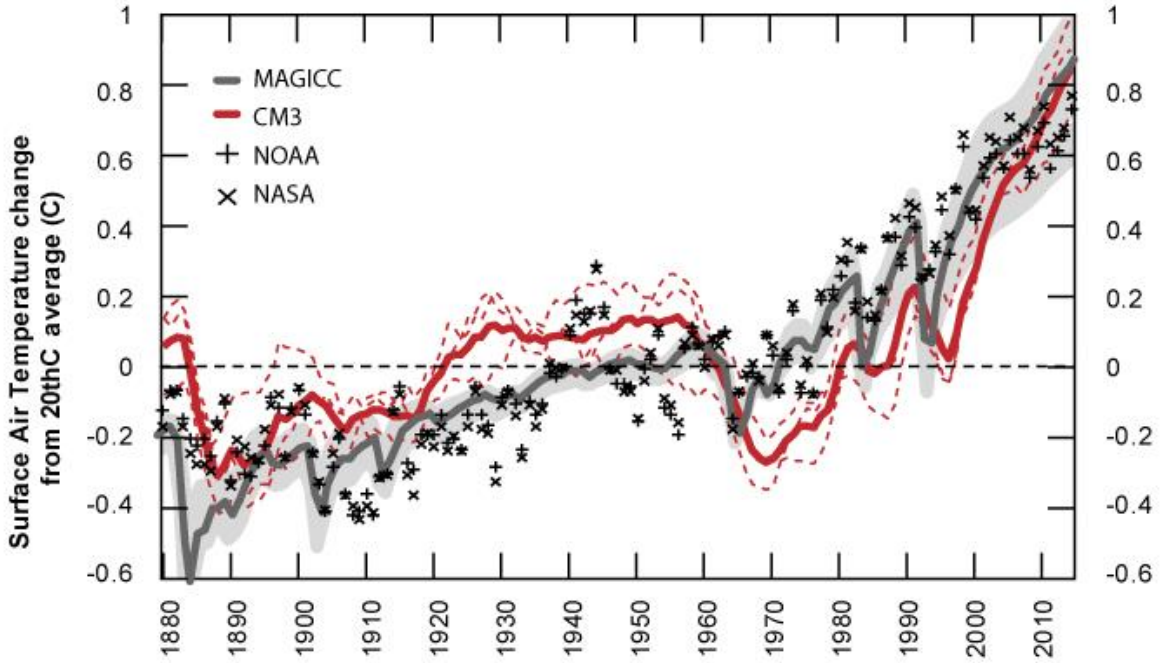

Figure 5. All forcing global-mean surface air temperature responses in ºC for CM3 (solid red line) and MAGICC (solid grey line) model simulations as compared to observations by NOAA (+) (https://data.giss.nasa.gov/gistemp/) and NASA (x) (https://www.ncdc.noaa.gov/cag/time-series/global). All annual temperature anomalies shown as change from 20th Century average for each dataset. Individual initial condition-driven ensemble members for CM3 runs shown in thin dashed red lines. Physics-driven ensemble-member range for MAGICC shown as shaded grey. CM3 data are 5-year running means.

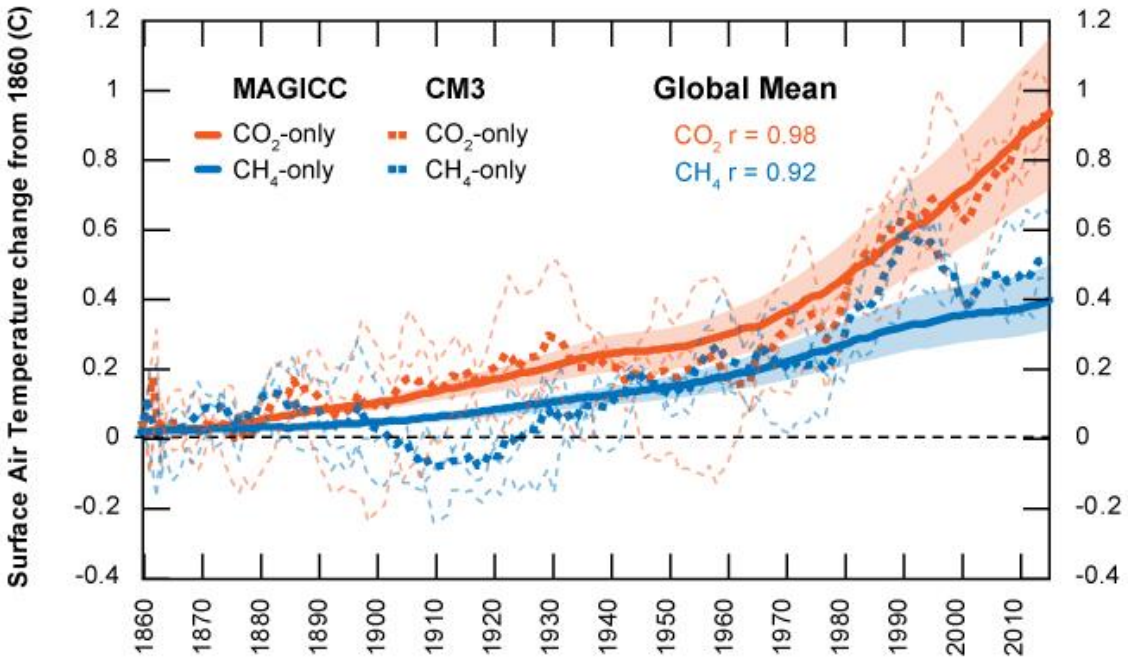

Figure 6. Global mean surface air temperature responses in ºC for CM3 (dashed line) and MAGICC (solid line) model derived simulations – CO_2-only (orange) and methane-only (blue). Individual initial condition-driven ensemble members for CM3 runs shown in thin dashed lines. Range for MAGICC physics-driven ensemble members shown in shaded colours. CM3 data are 5-year running means. Correlation coefficient between MAGICC and CM3 temperature responses are also shown.

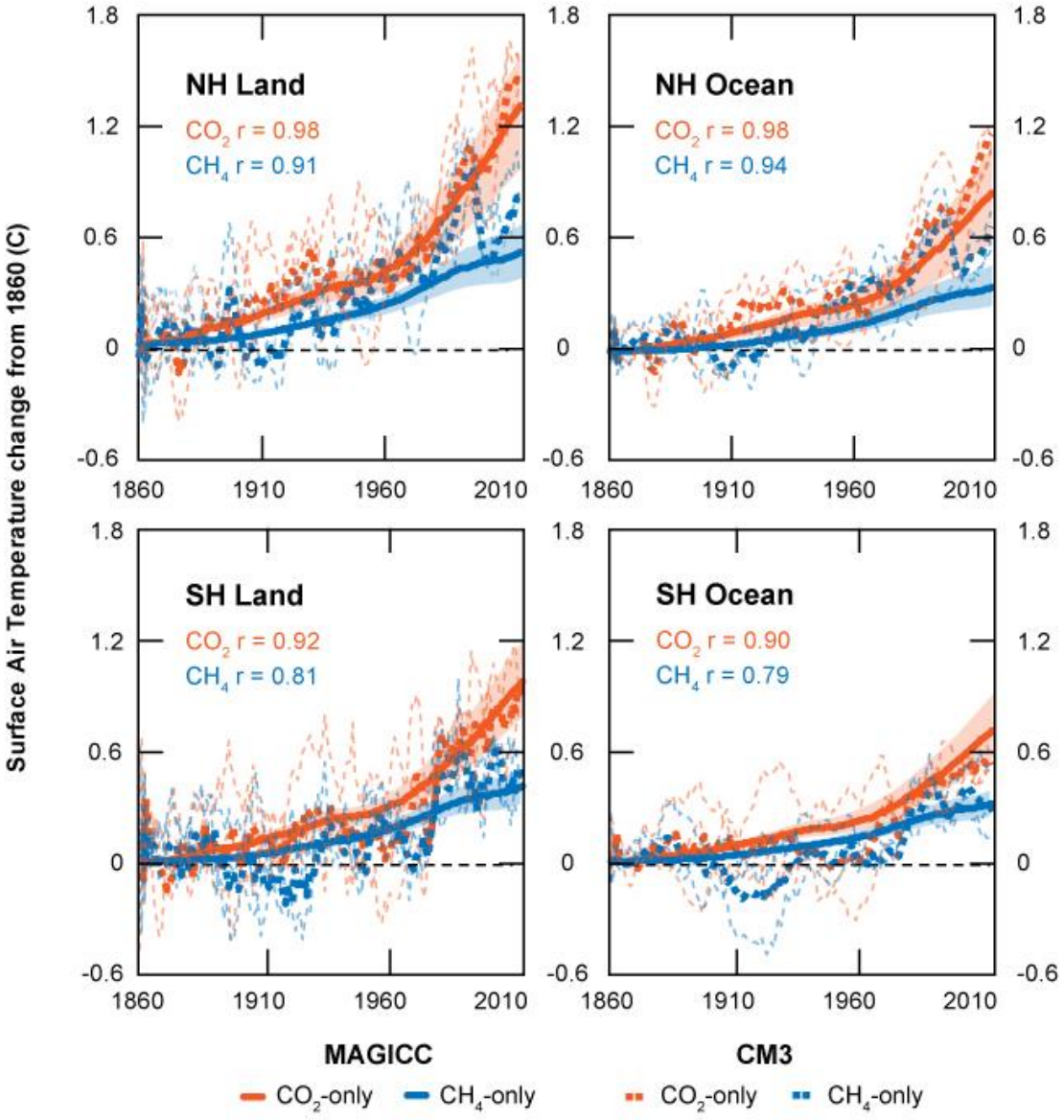

Figure 7. Regional surface air temperature responses in ºC for CM3 (dashed line) and MAGICC (solid line) model indirect simulations – CO_2-only (orange) and methane-only (blue). Individual initial condition-driven ensemble members for CM3 runs shown in thin dashed lines. Range for MAGICC physics-driven ensemble members shown in shaded colours. CM3 data are 5-year running means. Correlation coefficient between MAGICC and CM3 temperature responses are also shown.