We thank the reviewers for their helpful comments, which have led us to a substantially improved version of the paper. Here, the reviewers' comments are shown in boldfaced black text, and our responses are shown in non-boldfaced blue text. The page and line numbers to which we refer in our responses correspond to the updated manuscript (the comments of all reviewers are taken into account in this updated manuscript).

First and foremost, we confirm that the tropospheric chemical mechanism in GISS ModelE2 is not CBM04. The original manuscript version contained an incorrect oversimplified description of the tropospheric chemistry scheme in GISS ModelE2 that has caused our Reviewers confusion and understandable concerns. We understand that using an old-fashioned chemical mechanism developed 25 years ago for urban polluted high-NOx environments would be an inappropriate tool to apply to a study of large-scale isoprene emission perturbation in the tropics. The chemical mechanism in GISS ModelE2 has been substantially updated and improved over the past 15 years, for example, to account for important reactions, pathways, and species under low-NOx conditions (e.g. Shindell et al., 2003; 2006; 2013; Schmidt et al., 2014).

We now include a more detailed description of the chemical mechanism in Section 2.1 (ModelE2-YIBs description) (Page 4, Line 32):

"The troposphere features NO_X-O_X-HO_X-CO-CH_4 chemistry; an explicit representation of isoprene; and a lumped hydrocarbon scheme involving terpenes, peroxyacyl nitrates (PANs), alkyl nitrates, aldehydes, alkenes, and alkanes. The representation of hydrocarbons generally follows Houweling et al. (1998), which is originally derived from the Carbon Bond Mechanism-4 (Gery et al., 1989) and the Regional Atmospheric Chemistry Model (RACM; Stockwell et al., 1997), but includes several modifications aimed at representing the wide range of chemical conditions found in Earth's atmosphere, such as the addition of reactions important in low-NO_X conditions including representation of organic peroxy radical chemistry under low-NO_X conditions and introduction of organic nitrate chemistry. Shindell et al. (2013) describe in detail the recent updates to the tropospheric chemistry scheme, including the incorporation of acetone chemistry (Houweling et al., 1998) and the addition of terpene oxidation (Tsigaridis and Kanakidou, 2007). SOA formation is driven by NO_X-dependent oxidation of emissions of isoprene, monoterpenes, and other reactive VOCs following a volatility-based two-product scheme (Tsigaridis and Kanakidou, 2007). The formation of secondary inorganic aerosols, including sulfate (Bell et al., 2005; Koch et al., 2006) and nitrate (Bauer et al., 2007a), depend on both modeled oxidant levels and the availability of source gases. Primary aerosol types include dust (which provides a surface for heterogeneous chemistry; Bauer and Koch, 2005; Bauer et al., 2007b), black carbon, organic carbon, and sea salt (Koch et al., 2006). Stratospheric chemistry, introduced to the chemical mechanism by Shindell et al. (2006), includes nitrous oxide (N_2O) and halogen (bromine and chlorine) chemistry. Recent updates to stratospheric chemistry are summarized by Shindell et al. (2013) and include changes in the representations of polar stratospheric cloud formation (Hanson and Mauersberger, 1988) and heterogeneous hydrolysis of N_2O_5 on sulfate (Hallquist et al., 2003; Kane et al., 2001)."

Interdisciplinary work is challenging. We would like to emphasize the novel aspects of this project. (1) The land cover dataset for maritime Southeast Asia that we use in our study is built from an existing classification based on Landsat images (Gunarso et al., 2013). This dataset represents a wall-to-wall mapping of land cover in this region, including explicit representation of plantations of oil palm (high isoprene emitter) and rubber (high monoterpene emitter). Gunarso et al. (2013) used a consistent classification methodology for each year of their analysis, which has provided an internally consistent set of land cover maps for this period for this region. Other studies have investigated the atmospheric composition impacts from land cover change in this region: Ashworth et al. (2012) considered a projection of forest to oil palm conversion based on meeting future demand for biofuels; Warwick et al. (2013) considered the total conversion of Borneo to oil palm from forest; and Silva et al. (2016) considered the impact of 2010 oil palm cover relative to an oil-palm-free landscape in addition to considering future projections of oil palm. We consider the impacts of actual historical land cover change, which is clearly different than Ashworth et al. (2012) and Warwick et al. (2013). The Silva et al. (2016) study imposes oil palm expansion by overlaying an oil palm map for 2010 on a separate 16-PFT land cover distribution; this is a different methodology than we apply here, where we apply an internally consistent set of maps developed using a wall-to-wall classification methodology. (2) We have developed the global climate model code to add four additional land cover type PFTs, focusing on land covers that are pervasive in maritime Southeast Asia, including oil palm and rubber plantations. Previous studies have focused only on the impacts of oil palm expansion. (3) We consider the impacts of land-cover-change-driven changes in emissions of both isoprene and monoterpenes. The study by Silva et al. (2016) presumably includes dynamic changes in monoterpene emissions for the land covers that are displaced by oil palm, but their one new land cover type – oil palm – only has the isoprene emission capacity altered relative to the forest land cover type. Ashworth et al. (2012) and Warwick et al. (2013) consider only isoprene emission changes. (4) We directly quantify the global radiative forcing induced by ozone and SOA changes driven by historical land cover change in this region using a coupled global land-chemistry-climate model framework with the embedded radiative transfer model developed by A. Lacis and J. Hansen in GISS ModelE2 (e.g. Schmidt et al., 2014). (5) We provide new climate policy metrics for global ozone radiative forcing per Mha land cover change in the tropics. (6) We quantitatively identify that important factors driving uncertainty in the forcing include (a) uncertainty in the magnitude of the isoprene BER for oil palm and (b) uncertainty in the areal extent of oil palm expansion. Using an analysis based on fixed SOA yields, we additionally show that the sign of the net forcing is sensitive to uncertainty in the SOA yield from BVOCs.

Responses to Reviewer #1

The authors present the findings of a global modeling study probing the impacts of historical land cover change on the islands of maritime SE Asia with a particular focus on the expansion of oil palm plantations at the expense of natural forest. They apply a chemistry-climate model with interactive land surface to investigate the resulting changes in BVOC emissions and atmospheric composition in the region. In line with previous studies they conclude that changes in surface concentrations of the air pollutants / short-lived climate forcers, ozone and secondary organic aerosols (SOA), are negligible. However, they demonstrate that due to

strong convection in the tropics, upper tropospheric concentrations are more strongly affected and calculate the radiative forcing associated with these changes, showing that land cover change over this 20-year period in this region may have resulted in local changes in radiative balance.

On the whole this is a carefully implemented study with a reasonable selection of simulations designed to probe some of sensitivities of the model to their assumptions of land cover and vegetation characteristics. Their findings are generally well-presented. There is no doubt that the issue of tropical forest loss and / or degradation is of major global importance with both air quality and climate, and maritime SE Asia is a region which is experiencing rapid and extensive changes in land use.

However, I do have a number of reservations regarding their methodology, some of the assumptions made and the style in which they have presented some of their results. At present I feel that these are of sufficient concern to preclude publication.

Principal among these is the coarse resolution of the model used; a global model at 2x2.5 degree is not sufficiently fine resolution to adequately resolve the complex terrain or the heterogeneity of land cover, emission sources and chemical background conditions. NOx emissions have also rapidly increased in this region and the land cover changes included in this study will also introduce further changes. Given the sensitivity of ozone production and loss and SOA formation to the relative abundance of NOx and VOCs finely resolved spatial distributions are required to correctly diagnose both the direction and the magnitude of the changes in ozone concentration in particular.

My second major concern is the chemistry mechanism included in ModelE2-YIBs which the authors describe as based on CBM-4. CBM-4 was developed in the late 1980s and early 1990s at a time when the atmospheric chemistry community was principally focused on urban air quality and inorganic pollutants. The limited detail that the authors provide here suggests that the mechanism has not been updated to include the recent (i.e. post-2008) improvements in our understanding of isoprene oxidation under conditions of high BVOC and relatively low NOx concentrations, conditions that must apply to large parts of the region under study. The same applies to monoterpene chemistry and the formation of biogenic SOA from both isoprene and monoterpene oxidation products. Without these updates it is hard to have confidence in the modeled changes in atmospheric composition arising from changes in BVOC emissions and concentrations.

Finally, I find that the manuscript is highly skewed to changes in isoprene and ozone, with monoterpene and SOA impacts rarely mentioned in the main text. However the final figures of radiative forcing include the forcing due to changes in SOA. A full discussion of monoterpenes and SOA is therefore needed in the main text.

More detailed comments are given below.

1. p1 L22 - Could the authors provide a map of the region to indicate what they are describing as "maritime SE Asia" and "the maritime continent"

We provide Figure S2 (previously known as Figure S1), which shows the applied land cover changes. In Figure 1a, we analyze the surface ozone impacts over a wider region. Additional maps of the region are shown in Figures S3–S6 .

2. L22 - It would be useful if the authors could provide some sense of scale. What proportion of Indonesia as whole is 4.5Mha? Or perhaps more relevant, what proportion of the natural forest does this represent?

Good suggestion. We have modified this sentence (addition is bolded; Page 1, Line 24): "More than 4.5 Mha of natural forest were cleared in Indonesia alone over 2000–2010, **which is a loss of 4.6 % of year 2000 Indonesian natural forest cover** (Margono et al., 2014)."

Reference:
Margono, B.A., Potapov, P.V., Turubanova, S., Stolle, F., and Hansen, M.C.: Primary forest cover loss in Indonesia over 2000–2012, Nat. Clim. Change, 4, 730–735, doi: 10.1038/nclimate2277, 2014. (Their Table 1 reports total natural forest area in Indonesia in 2000 as 98.4 Mha.)

3. L26 - It may have quadrupled but it started from a very low base; this is one of a number of times that the authors have tended toward dramatising the results.

The reviewer appears to be somewhat missing the point here. Firstly, the areal cover in 1990 is implicit in the sentence: "The amount of land area planted in oil palm in Indonesia and Malaysia nearly quadrupled over 1990–2010, reaching 13 Mha by 2010 (Gunarso et al., 2013)." We modify the sentence to make the areal cover in 1990 now explicit (Page 1, Line 27): "The amount of land area planted in oil palm in Indonesia and Malaysia increased from 3.5 Mha in 1990 to 13 Mha by 2010 (Gunarso et al., 2013)." Secondly, we don't agree that this statement can be "one of a number of times that the authors have tended toward dramatizing the results" because (1) we are not discussing any project results in the Introduction Section and (2) in the Introduction section, we are describing the background motivation for the study as an opportunity for a real world case study during which a large-scale human-induced land cover change happened in the Earth system that has driven a regional-scale increase in isoprene emission.

4. p2 L7-9 - In fact, Ashworth et al. reported the change in the total tropospheric burden of ozone and SOA before focusing on surface changes and Warwick et al. present altitudinal plots of the changes in some trace gases.

We have expanded the Introduction Section, including highlighting the important findings of both the Ashworth et al. (2012) and Warwick et al. (2013) studies, in addition to another relevant study (Silva et al., 2016).

The Ashworth et al. (2012) study reports tropospheric burden changes for ozone and OH, but does not report changes for any specific altitude other than the surface. We do not find any mention of non-surface-level changes in SOA in Ashworth et al. (2012). The Warwick et al. (2013) study plots PAN and OH changes as a vertical cross-section at the equator from the surface to 90 hPa and the spatial distribution of PAN changes at 500 hPa; in addition, they report the peak ozone change at 500 hPa over Borneo, but they do not report any other non-surface-level ozone changes, which are particularly important for our study.

We have added:

(1) Page 4, Line 7: "In response to isoprene emission enhancements associated with total conversion of vegetated land to oil palm on the island of Borneo, Warwick et al. (2013) simulate a 20% increase in ozone at 500 hPa over Borneo and a 20% increase in peroxyacetyl nitrate (PAN) at 500 hPa downwind of Borneo over the Pacific Ocean. PAN is an organic nitrate that can undergo long-range transport before releasing its reactive NO_X moiety (Moxim et al., 1996), providing a means for ozone formation in remote environments (Kotchenruther et al., 2001). The results of Warwick et al. (2013) suggest that regional isoprene emission changes have the capacity to alter ozone concentrations in the free troposphere and, therefore, induce a radiative forcing."

(2) Page 3, Line 33: "Ashworth et al. (2012) speculated a small global forcing impact from the increased isoprene emissions in their land-use change scenario, based on the small simulated global changes in the tropospheric burdens of ozone and the hydroxyl radical (OH). However, no study has directly quantified the global radiative impacts associated with the induced changes in atmospheric composition."

5. L20-21 - This is the first mention of monoterpenes (aside from the abstract). I suggest for the authors also to discuss the atmospheric chemistry and composition effects of monoterpenes as per isoprene in the previous paragraph. For instance the surface flux measurements reported from the OP3 field study (Langford, Misztal) showed that natural forests are much stronger emitters of monoterpenes than oil palm plantations. And the previous investigations also included changes in monoterpene emissions which is not clear in L7-9 as the preceding lines had focused exclusively on isoprene.

The changes in monoterpenes and SOA seem to very much be of lesser importance to the authors than changes in isoprene and ozone here and throughout the manuscript. While I accept that the changes are smaller they still contribute to the overall radiative forcing reported by the authors and should be given full coverage in the main text and not just the SI

The reviewer is correct in that we mainly focus on isoprene emission changes because of the larger change in isoprene (+6.5 TgC y^{-1}) relative to the change in monoterpenes (-0.5 TgC y^{-1}). Likewise, we deliberately focus on ozone more than SOA because of the stronger simulated radiative forcing from the ozone perturbations. Hence, the paper is not skewed. For example, the paper would be skewed if the primary focus was monoterpenes-SOA.

That said, we agree with the reviewer that the monoterpenes and SOA need to be given appropriate coverage in the main text and not just the SI (additions in bold, deletions crossed out; Page 2, Line 11): "Above-canopy flux measurements **taken in Borneo in 2008** indicate that, compared to the natural forests of maritime Southeast Asia (MSEA), oil palm plantations are much stronger emitters of the biogenic volatile organic compound (BVOC) isoprene (C_5H_8), **with mean midday fluxes about five times stronger from oil palm** (Langford et al., 2010; Misztal et al., 2011). The simultaneous large-scale contraction of low-isoprene-emitting natural forest area and expansion of high-isoprene-emitting oil palm plantations suggests a land-cover-change-driven increase in regional isoprene emissions over recent decades (Silva et al., 2016; Stavrakou et al., 2014). **Measurements indicate that the forests of MSEA emit monoterpenes, a class of BVOCs with chemical formula $C_{10}H_{16}$, but find negligible monoterpene emissions from oil palm (Langford et al., 2010; Misztal et al., 2011). Both** isoprene **and monoterpenes are** ~~is a~~ precursors to the short-lived climate pollutants tropospheric ozone (Atkinson and Arey, 2003) and secondary organic aerosols (SOA) (Carlton et al., 2009; **Friedman and Farmer, 2018**); **as such, perturbations in regional isoprene and monoterpene emissions serve as an additional mechanism by which regional land cover change can affect air quality and climate**."

Added reference:
Friedman, B. and Farmer, D.K.: SOA and gas phase organic acid yields from the sequential photooxidation of seven monoterpenes, Atmos. Env., 187, 335–345, doi: 10.1016/j.atmosenv.2018.06.003, 2018.

With respect to the previous studies, it is our understanding that: Ashworth et al. (2012) only consider emission changes for isoprene, but do consider the impact that the resulting changes in atmospheric composition have on monoterpene processing; Warwick et al. (2013) likewise consider only isoprene emission changes for forest to oil palm conversion (their paper does not explicitly state how the atmospheric composition changes from the isoprene emission perturbations impact the simulated monoterpene chemistry, although this is presumably taken into account); and Silva et al. (2016) alter only the isoprene emission capacity (and not the monoterpene emission capacity) of their new oil palm land cover type relative to the forest PFT, but their results presumably take into account the effect of monoterpene emission changes associated with the loss of the various land covers to oil palm.

6. L24 - Does this mean that the authors have only conducted a series of atmosphere-only model simulations? So there are no climate / land surface feedbacks included on-line?

Atmosphere-only run is a standard technical term widely used by the World Climate Research Program (WCRP) Coupled Model Intercomparison Project (CMIP). It means that the global climate model uses prescribed observed sea surface temperatures and sea ice fields. Thus, the climate model does not have a fully coupled dynamic ocean. The term is in common usage in the global climate modeling community. Atmosphere-only simulations can be dynamically coupled to atmospheric chemistry and the land surface, as in our work.

7. L24-27 - Actually I am now confused as to exactly what model simulations were performed. The authors have referred to atmosphere-only, chemistry-climate, and land surface models here. Exactly what configuration is being used?

The reviewer is unfamiliar with standard terminology in the global climate and atmospheric chemistry modeling communities. See response to Point (6). Atmosphere-only means prescribed sea surface temperatures and sea ice fields. Atmosphere-only simulations can be dynamically coupled to atmospheric chemistry and the land surface, as in our work. Our description of the model set-up and configuration is clear, complete, and appropriate. No further changes are needed here.

8. L27 - 2 deg x 2.5 deg is too coarse to adequately resolve the complexity and heterogeneity of the land mass and land cover in this region particularly given the sensitivity of BVOC oxidation and ozone production rate to VOC:NOx ratio.

The reviewer is raising a longstanding query that concerns the entire large-scale global climate and chemistry mathematical modeling communities, way beyond the scope of this study, regarding what is actually needed in a global model (with associated limited computational resources) to reproduce large-scale composition impacts versus a highly localized mathematical representation of every real process on the ground tending to continuous resolution, many of which do not actually matter to the global radiative impact of ozone and SOA. This conflict commonly emerges between communities engaged in large-scale mathematical modeling versus communities engaged in local ecosystem-scale measurements. Nobody is ever surprised when it comes up in interdisciplinary work.

The reviewer's comment applies to the use of all global chemistry-climate (CCM) and global chemistry-transport (CTM) models for the study of the global radiative impacts of regional-scale changes in short-lived emission precursors. The "complexity and heterogeneity of the land mass and land cover and the sensitivity of BVOC oxidation and ozone production rate to VOC:NOx ratio" are NOT issues unique to the MSEA region. Undeniably, these issues are important in all chemical regimes and regions of the world where the large-scale atmospheric responses to short-lived emission precursor perturbations are being studied. State-of-the-science global CCMs and CTMs typically have horizontal resolution 1-2° latitude/longitude. The model horizontal and vertical resolution applied in this study is comparable to global CCMs and CTMs currently being used in the WCRP CMIP6 Aerchem-MIP and RF-MIP in support of the

forthcoming IPCC AR6 assessment, and the Task Force on Hemispheric Transport of Air Pollutants (HTAP). These international assessment programs each employ dozens of global models with 1-2° latitude/longitude resolution to quantify the impacts of local and regional short-lived precursor emission changes, including VOCs, in very different regions and regimes. It is a moot point that global CCMs and CTMs do not fully resolve the complexity and heterogeneity of land mass and land cover and other sub-grid phenomena. The models parameterize these conditions and processes.

By the reviewer's own logic, thousands of peer-reviewed publications in high-caliber journals, HTAP, Aerchem-MIP and RF-MIP, and short-lived climate forcers in IPCC AR6/AR5/AR4 are invalid. We do not agree. The goals of this work are to quantify the global radiative forcing of ozone and SOA changes due to the isoprene emission injection and altered BVOC fluxes as a result of recent human-induced land cover change in MSEA. Therefore, we have used a model framework that has been designed to simulate the global radiative forcing impacts from local and regional short-lived emission precursor perturbations, including, but not limited to, assessments by HTAP, Aerchem-MIP, RF-MIP, and a wide range of other international multi-model assessment programs over the past 20 years.

9. L31 - I have reservations whether the chemistry mechanism employed here is suitable for the conditions encountered in this region. Although it is rapidly developing with the concomitant increases in anthropogenic emissions, much of island areas of the region are still low-NOx, high-VOC regimes. Older chemical mechanisms were designed for the typical chemistry encountered in mid- to high-NOx urban / industrial areas and considerable understanding has been gained of the very different oxidation pathways of (particularly) isoprene under lower NOx conditions. Have any of these updates been included in the chemistry here?

Please see comment at the top of this document. In the original manuscript version, we neglected to provide a detailed enough description of the current chemical mechanism. Certainly, we too would have major reservations about a study using CBM04 to quantify composition impacts of a large isoprene emission injection in the tropics. The revised manuscript now includes a more detailed and accurate description of the chemical mechanism.

10. p3 L8 - Are the monoterpenes emitted as a single lumped monoterpene species? Or at least in part speciated (e.g to specifically include a-pinene, b-pinene, d-limonene and others as is often done)? It should be noted that the monoterpene emissions algorithms included in Lathiere et al are in fact the Guenther et al. algorithms from 1995; at the very least this paper should be referenced here. Also, these algorithms assume that monoterpene emissions are entirely temperature dependent whereas more recent field measurements have shown that many species emit a proportion of monoterpenes directly (i.e. monoterpene emissions exhibit both light and temperature dependency, see e.g. Steinbrecher et al, Guenther et al. 2012). Are the authors confident that this is not the case for SE Asian plant species?

We have added the Guenther et al. (1995) reference and a brief discussion of light-dependency. ModelE2 applies a lumped monoterpene species (Page 6, Line 28): "Temperature-dependent leaf-level monoterpene emissions, functionally α-pinene, likewise vary by ecosystem type, similarly through prescription of PFT-specific basal emission rates (Guenther et al., 1995; Lathière et al., 2006). Recent work suggests that tropical monoterpene emissions exhibit both light and temperature dependency (Guenther et al., 2012; Jardine et al., 2015, 2017) that is not included in the emission algorithm here but may be explored in future work."

Added references:

Guenther, A., Hewitt, C.N., Erickson, D., Fall, R., Geron, C., Graedel, T., Harley, P., Klinger, L., Lerdau, M., McKay, W.A., Pierce, T., Scholes, B., Steinbrecher, R., Tallamraju, R., Taylor, J., and Zimmerman, P.: A global model of natural volatile organic compound emissions, J. Geophys. Res.-Atmos., 100, 8873–8892, doi: 10.1029/94JD02950, 1995.

Jardine, A.B., Jardine, K.J., Fuentes, J.D., Martin, S.T., Martins, G., Durgante, F., Carneiro, V., Higuchi, N., Manzi, A.O., and Chambers, J.Q.: Highly reactive light-dependent monoterpenes in the Amazon, Geophys. Res. Lett., 42, 1576–1583, doi: 10.1002/2014GL062573, 2015.

Jardine, K.J., Jardine, A.B., Holm, J.A., Lombardozzi, D.L., Negron-Juarez, R.I., Martin, S.T., Beller, H.R., Gimenez, B.O., Higuchi, N., and Chambers, J.Q.: Monoterpene 'thermometer' of tropical forest-atmosphere response to climate warming, Plant Cell Environ., 40, 441–452, doi: 10.1111/pce.12879, 2017.

11. L15-19 - How were emission factors assigned to these additional land cover types? How do they differ from the standard land cover in this region in the default land surface map? Again this is critical to the results and should be included in the main text and not just the SI.

On (Page 6, Line 22), we state: "For each PFT, the isoprene emission rate depends linearly on the fraction of electrons available to undergo isoprene synthesis, **the calculation of which requires prescription of a PFT-specific leaf-level isoprene basal emission rate (BER) at standard conditions.**"

We have moved the Table of model parameters (previously known as Table S2 in the Supplement) to the main text (now known as Table 1).

On Page 9, Line 20, we removed the list of references from this sentence (as this information is found in the footnotes of Table 1, now in the main text) and re-phrased to better describe what is found in the table: "Table 1 shows, for the new land cover types, the assigned physical parameters (including LAI and vegetation height), photosynthetic parameters, and leaf-level basal emission rates of isoprene and monoterpenes."

We describe the relationship between the isoprene BERs for the standard and new rainforest PFTs where this information is critical (Page 13, Line 10): "In this sensitivity analysis, the dipterocarp forest **isoprene** BER is increased by a factor of 12, **making it equivalent to the isoprene BER assigned to the standard evergreen broadleaf forest PFT in YIBs**."

12. L31-32 - Of real importance to this study is the previous performance of the YIBs model in this region; the 2013 study was global. Do the referenced comparisons include field sites in maritime SE Asia?

The 2013 global evaluation paper did include time-varying OP3 Borneo field measurements (e.g. Langford et al., 2010). The point of referencing the global-scale evaluation against a wide range of different ecosystems and regions is to demonstrate that the model has reasonable isoprene emission performance over a range of different ecosystems and regions. The present manuscript provides a comparison of oil palm and forest isoprene fluxes to those from the OP3 campaign in Borneo (Page 22, Line 8; Page 22, Line 25).

13. p4 L14-15 - It seems odd to go the lengths of using 30m x 30m resolution land cover data in a model running at 2 deg/ x 2.5 deg

The 30 m x 30 m resolution land cover dataset (i.e., the dataset of Gunarso et al., 2013) is re-gridded to the model resolution of 2° latitude x 2.5° longitude before application to the model (Page 8, Line 27). The purpose of applying the high-resolution dataset is because, as far as we know, this is the only land cover dataset available for this region that employs a wall-to-wall classification methodology that provides multiple years of data (using a consistent classification methodology for each year) and includes several land covers that are prevalent in Southeast Asia (e.g., oil palm and rubber plantations). The availability of such a dataset prevents us from needing to build a single dataset out of multiple datasets that were potentially derived using different classification methodologies or are from different time periods.

14. L20-26 - Please clarify. Are you saying that in 1990 the only land cover data available shows natural forest (or whatever) in locations that were shown as oil palm in 2000 and 2010? What fraction of data is missing? Of the 1990 data what fraction is converted to oil palm by 2000 and 2010? Of the missing data what fraction is "converted" to oil palm by 2000 and 2010? It would be useful to have a feel for how substantial the "likely underestimation" might be.

We have clarified the language (modifications bolded, Page 8, Line 19): "The Gunarso et al. (2013) classification for 1990 for Indonesia is likewise incomplete; in this dataset, the pixels classified for 1990 are principally those that are **oil palm in 1990 or eventually become oil palm**."

Thus (Page 8, Line 23): "Indonesian oil palm cover in 1990 is accurate within the limits of the classification methodology."

The rest of Indonesia is largely unclassified in 1990, as described, which is why we apply the year 2000 land cover to these pixels.

15. L30 - Is dirt equivalent to the "bare ground" classification included in other land surface schemes?

Fixed. We have amended the text to state "bare ground" rather than "dirt."

16. p5 L3 - The authors say that these are "minor land cover types". Again it would be useful to be provided with sufficient information to judge just how minor. What fraction of land is included in these 5 types in Gunsaro et al classification?

These minor land cover types account for 2.8% of pixels in both 1990 and 2010.

17. L8-13 - Again it would be good to have an idea of the likely underestimation, and this should be relatively easy for the authors to achieve by applying an LAI reduction, as described, to the areas classified as "disturbed" in Gunsaro.

For the forest class, around 43% is disturbed, while around 57% is undisturbed (these fractions are largely consistent across years). Dietz et al. (2007) report LAIs for various disturbance levels: undisturbed (6.2 m^2 m^{-2}), removal of small-diameter trees (5.3 m^2 m^{-2}), and removal of large-diameter trees (5.0 m^2 m^{-2}). Based on these LAIs, the mean LAI for the forest class (47% disturbed, 57% undisturbed) would be: (1) 0.57 x 6.2 m^2 m^{-2} + 0.43 x 5.3 m^2 m^{-2} = 5.8 m^2 m^{-2} (assuming that the disturbed forest falls closer to the small-diameter removal category) and (2) 0.57 x 6.2 m^2 m^{-2} + 0.43 x 5 m^2 m^{-2} = 5.7 m^2 m^{-2} (assuming that the disturbed forest falls closer to the large-diameter removal category). In our simulations, we assign a forest LAI of 6.0 m^2 m^{-2}, based on measurement of a natural forest plot in Malaysian Borneo (Fowler et al., 2011), which is an area included in our land cover change analysis. Thus, our assigned value is only about 3–5% higher than these rough estimates, which is a good approximation considering that we do not have any information about the level of disturbance of the "disturbed" forest patches in the land cover change dataset that we apply (that is, the classification of Gunarso et al. (2013)). In the Gunarso et al. (2013) classification, a "disturbed" forest patch has a reduced basal area with evidence of clearing or logging. Such classifications are not uncommon; for example, Margono et al., Nature Climate Change, 2014, use a "primary degraded forest" class, in which the forest has been fragmented or experienced selective logging or other disturbance.

18. L21 - As noted above, Table S2 should be in the main text as these parameter values are critical to the results. The notes regarding their derivation can be left in SI. The values for the "standard" PFTs in YIBs for this region should also be shown in this table for comparison.

We have moved this table and the footnotes, which are an integral part of the table, to the main text (now known as Table 1).

19. L27-34 - There is a real mishmash of years for the various datasets. As the simulations are being conducted for a nominal 2010 (i.e. that is the climatology) with 1990 or 2010 SE Asia landcover why introduce further limitations / discrepancies by using Y2000 landcover for the rest of the world with vegetation characteristics derived using Y2000 meteorology only to change to 2010?

We assume that the global radiative forcing impacts by ozone and SOA due to oil palm expansion in MSEA are insensitive to changes in the background land cover state outside of the MSEA region over the 1990–2010 period. Unfortunately, we do not always have available all observational or modeled data for each year for each boundary condition for model runs, which means that we sometimes need to combine datasets in appropriate ways to run simulations. Here, we use a dataset for 2000, which falls within the era of interest (1990–2010). We use the year 2000 rest-of-world land cover dataset specifically because we already had available the PFT-specific vegetation height parameters for the set of PFTs used in ModelE2-YIBs at the resolution used in ModelE2-YIBs. As we describe in the paper, we obtained the PFT-specific height parameters applied to the rest of the world vegetation from an existing 140-year simulation run with our model. This 140-year simulation was run using dynamic carbon allocation and applied the same rest-of-world land cover distribution that we apply here. Using this configuration, a 140-year simulation requires at least a few months of run time, which accounts only for the actual time that the model is integrating and does not include time spent in the simulation queue between re-submissions (since our cluster allows only one week of run time before the simulation must be re-submitted, the additional time spent in the run queue can be substantial). With unlimited computational resources, we could run an additional century-long simulation for year 1990 or 2010, but we don't have access to these resources, and, more importantly, it is unlikely that switching to 1990 and 2010 background land cover datasets has any meaningful influence on the results here. The benefit of doing so is not clear because we hold static the rest-of-world land cover map and physical vegetation characteristics (because we need to isolate the impacts of MSEA regional land cover change) and this dataset is a reasonable approximation of land cover and vegetation characteristics for this 1990–2010 era.

20. p6 L33-34 - Could the authors please clarify how the simulations were driven with the meteorology? Was the same climate / meteorology applied for 13 years? Because there will be an effect of inter-annual variability on emissions, chemistry and therefore O3 and SOA formation; how has this been accounted for? Is this what the authors have attempted to do via the additional simulations?

We have removed the incorrect description of the nudged winds. The quantified standard deviations (e.g., radiative forcing in Table 5 on Page 21) are based on internal interannual variability in the climate model. We have additionally performed a sensitivity simulation to assess the impact of using a different background climate (including emissions year) on the forcing results (Table 5 on Page 21).

21. p7 L4-6 - This is the case for all current isoprene emissions models which are linked to PAR, T, CO2, soil moisture, etc. Please clarify what aspect the authors mean is the case "because" it is interactively linked OR remove the word "because"

To improve clarity, we have re-phrased this (additions bolded, deletions crossed out; Page 12, Line 14): "~~Because~~ Isoprene production in ModelE2-YIBs is ~~interactively linked to~~ **calculated as a semi-mechanistic function of** photosynthetic carbon assimilation (Unger et al., 2013). Isoprene emissions are sensitive to simulated changes in the parameters that affect photosynthesis, including the background climate state (**e.g., temperature, PAR, and soil moisture**) and **the** atmospheric CO_2 concentration."

22. L6-7 - Please give more detail of how monoterpene emissions are sensitive to climate as per isoprene

We have changed "climate" to "temperature" (Page 12, Line 17): "Simulated monoterpene emissions are likewise sensitive to temperature shifts (Lathière et al., 2006)."

23. L9-11 - But changing the landcover will also affect e.g. NOx emissions, either due to changes in fertiliser application or to changes in natural soil emissions. How have the authors accounted for this?

Because again the resolution of the global model will not be sufficient to pick up changes such as this simply by running a sensitivity test with a different background atmosphere.

The reviewer raises a good point. We account for anthropogenic changes in NOx emissions and all other short-lived emission precursors by applying the MACCity inventory for anthropogenic emissions of carbonaceous aerosols and reactive gases (Granier et al., 2011). The MACCity inventory is partially based on the ACCMIP inventory, which is based on a multitude of global- and regional-scale emission inventories (Lamarque et al., 2010). MACCity includes agricultural NOx emissions. Climate-sensitive lightning NOx and soil NOx emissions are included in the simulations. Atmospheric NOx measurements in the region are extremely limited. A possible future work direction beyond the scope here is to exploit satellite NOx data to learn more about the NOx levels in the region.

24. L28-30 - Why have the authors not used the measured emission rate in the first instance?

Our model requires a leaf-level BER (YIBs has its own canopy up-scaling scheme consistent for carbon, water, energy, and BVOCs). Therefore, we adopted a strategy that maximizes use of the

limited available BVOC flux data in the region. First, we implemented published leaf-level isoprene BERs to all PFTs including oil palm (Table 1; now in the main text). Then, we used the raw measured fluxes (not canopy-level BERs) from the OP3 campaign to evaluate and validate the model's simulated above-canopy fluxes (Page 22, Line 8; Page 22, Line 25). This strategy is more physically realistic, and provides a better benchmark than, for example, artificially forcing the model to reproduce the OP3 canopy-scale BERs as a boundary condition.

25. L30-32 - Why? The authors specifically introduced this land class because measurements had shown that the global emission factors were not suitable. The work reported in Langford and Misztal suggested that emission factors were out by a factor of 3 so using 12 seems rather extreme.

The rationale is simply a sensitivity study to examine the impacts when the forest emits with a default isoprene BER for tropical rainforest, that is where the factor of 12 comes from. See response to point (11).

26. p8 Table 2 - this seems to imply that the isoprene emission factor applied to oil palm is as measured in the standard run but half measured in the OPber sensitivity tests which appears to contradict what the authors have described in the previous page.

The values reflect the difference between the canopy-scale and leaf-level BERs for oil palm isoprene emission.

27. p9 L3-4 - It would also be good to see how well 1990land_base and 1990land_1990atm GPP compare with measured GPP

We amended the text to state (Page 14, Line 9): "Simulated global gross primary production (GPP) for 2010 is 124 PgC y^{-1} (simulation 2010land_base), which almost precisely matches an estimate derived from flux-tower measurements that is representative of 1998–2005: 123 ± 8 PgC y^{-1} (mean ± 1 standard deviation; Beer et al., 2010). The simulated 1990 global GPP of 108 PgC y^{-1} (simulation 1990land_1990atm) is outside of the 1-standard-deviation range of the observation-based mean, but falls within the 95% confidence interval (102–135 PgC y^{-1}; Beer et al., 2010)."

The small change in GPP from 1990–2010 land cover change (2010land_base minus 1990land_base) is described later in the text, so providing the value for 1990land_base here would be repetitive.

28. L5 - please define contemporary, because Table 5 in the Guenther paper contains estimates from early 90s to around 2008. Again it would be useful to see the emissions estimates for both 1990 and 2010 land cover and climates here.

The estimates from Guenther et al. (2012) Table 5 are from references that were published over the period 1995–2011. The table does not indicate the year represented by each estimate. However, the forcing datasets (e.g., those for "weather" and "LAI") listed in the table for each of the estimates suggest that the estimates are from the contemporary (modern day) period as opposed to future projections or the pre-industrial era. We use these estimates to show that the global emissions of isoprene and monoterpenes that are simulated in our study are reasonable. We also compare our 2010 isoprene estimate to another estimate representative of the 1971–2000 mean.

We have expanded the text to include our 1990 estimates (Page 14, Line 15): "The model estimates for 1990 (325 TgC y^{-1} isoprene and 90 TgC y^{-1} monoterpenes for simulation 1990land_1990atm) and 2010 (363 TgC y^{-1} isoprene and 77 TgC y^{-1} monoterpenes for simulation 2010land_base) fall within these ranges. Using the same process-based, leaf-level isoprene production algorithm employed in ModelE2-YIBs, although driven with different forcing datasets, Hantson et al. (2017) predict contemporary isoprene emissions (385 TgC y^{-1}; 1971–2000 mean) that are 18% higher than those predicted here for 1990 and only 6% higher than those predicted here for 2010."

29. L10-19 - Here and throughout, although the authors describe this as a study of how BVOC emissions changes have affected the region the manuscript is entirely dominated by consideration of isoprene. While this is understandable given that total regional isoprene emissions are more than 5x those of monoterpenes I think the paper would benefit from more consideration of monoterpene emissions and impacts as monoterpenes and isoprene have different effects on atmospheric composition and chemistry. I suggest the authors also pay careful consideration to their use of the catch-all BVOC as this study appears only to include isoprene and monoterpenes.

See response to Point (5). We will continue with the use of "BVOC" to describe isoprene and monoterpenes. There is a growing body of literature on the impacts of isoprene and monoterpenes on regional and global radiation budgets and short-lived climate forcers (e.g., Heald and Geddes, 2016; Hollaway et al., 2017; Scott et al., 2017, 2018; Unger, 2014a,b). To our knowledge, there is no current published evidence that any other BVOC species have statistically significant large-scale global and regional radiative effects. Because of their extremely short-lifetimes, it is likely that other highly reactive emitted compounds have much more localized impacts.

References:

Heald, C.L. and Geddes, J.A.: The impact of historical land use change from 1850 to 2000 on secondary particulate matter and ozone, Atmos. Chem. Phys., 16, 14997–15010, doi: 10.5194/acp-16-14997-2016, 2016.

Hollaway, M.J., Arnold, S.R., Collins, W.J., Folberth, G., and Rap, A.: (2017), Sensitivity of midnineteenth century tropospheric ozone to atmospheric chemistry-vegetation interactions, J. Geophys. Res.-Atmos., 122, 2452–2473, doi:10.1002/2016JD025462, 2017.

Scott, C.E., Monks, S.A., Spracklen, D.V., Arnold, S.R., Forster, P.M., Rap, A., Äijälä, M., Artaxo, P., Carslaw, K.S., Chipperfield, M.P., Ehn, M., Gilardoni, S., Heikkinen, L., Kulmala, M., Petäjä, T., Reddington, C.L.S., Rizzo, L.V., Swietlicki, E., Vignati, E., and Wilson, C.: Impact on short-lived climate forcers increases projected warming due to deforestation, Nat. Commun., 9:157, 1–9, doi: 10.1038/s41467-017-02412-4, 2018.

Scott, C.E., Monks, S.A., Spracklen, D.V., Arnold, S.R., Forster, P.M., Rap, A., Carslaw, K.S., Chipperfield, M.P., Reddington, C.L.S., and Wilson, C.: Impact on short-lived climate forcers (SLCFs) from a realistic land-use change scenario via changes in biogenic emissions, Faraday Discuss., 200, 101–120, doi: 10.1039/c7fd00028f, 2017.

Unger, N.: Human land-use-driven reduction of forest volatiles cools global climate, Nat. Clim. Change, 4, 907–910, doi: 10.1038/NCLIMATE2347, 2014a.

Unger, N.: On the role of plant volatiles in anthropogenic global climate change, Geophys. Res. Lett., 41, 8563–8569, doi: 10.1002/2014GL061616, 2014b.

30. L16-18 - Similarly to the previous comment, rubber plantations don't make such a strong contribution to total BVOC emissions (e.g. compared to shrubs). However they do appear to dominate the monoterpene budget and might therefore have a strong role in SOA formation rate and yield. I suggest re-phrasing this sentence to make this distinction clearer.

This is a good point, and we have re-phrased the sentence (Page 15, Line 3): "The strong contributions made by rubber and oil palm plantations to the regional monoterpene and isoprene budgets, respectively, underscore the importance of explicitly accounting for these land covers in regional land use and land cover change analyses."

31. L20-21 - but as previously noted by the authors, their assumptions in assigning land cover has likely led to an underestimation of deforestation. Please could the authors make some attempt to quantify the uncertainty in the changes in GPP. In addition to the method applied to fill data gaps and the non-inclusion of changes in LAI due to disturbance, the authors have used 2010 climatology in both cases which will affect the estimated GPP. I am assuming that the figure quoted here is based on difference between the two base simulations.

We purposefully apply the 2010 physical climate state in order to isolate the impacts of the human-induced land cover change only on global radiative forcing by ozone and SOA. For example, the physical climate changes themselves between 1990 and 2010 induce changes in ozone and SOA forcing.

32. L25-26 - this could perhaps be better phrased as the loss of dipterocarp forest is due to its replacement by another land cover; as this is often oil palm so overall isoprene emissions go up.

We keep the original phrase that is focusing on the changes in dipterocarp forest alone and useful to quantify (Page 15, Line 12): "The large loss of dipterocarp rainforest had little impact on isoprene emissions (-0.1 TgC y-1), as this PFT is a weak isoprene emitter."

33. L31 - I think the authors mean "Considering only the grid-cells that are majority . . ." as they then go on to give surface O3 concentrations in 2 sub-regions rather than ALL of the study area.

Fixed.

34. p10 L3-5 - These measurements would seem to support the low ozone concentrations simulated by the model over Malaysian Borneo; however I am not sure they provide evidence of ozone concentrations over ALL forested areas in the region particularly as the authors are comparing annual mean concentrations with measurements made for one particular (short) period.

Good point. However, we only have measurements for Malaysian Borneo, so we use them as a proxy for the forested parts of the entire region.

And related to this, are the authors intending to imply that they simulate much higher levels of ozone over the non-forested areas in the region? In which case, what are the average ozone concentrations for e.g. peninsular Malaysia which is far more industrialised? i.e. it is likely the case for many of the included grid cells that the proportion of the grid cell not occupied by forest in Borneo and New Guinea is ocean, whereas in peninsular Malaysia, etc many more will contain urban / industrial areas with higher NOx emissions.

Yes, this is clearly visible in Figure S4.

35. L7-8 - This would be a suitable place for the authors to emphasise the difference between the effects of monoterpenes vs isoprene, with isoprene oxidation more implicated in ozone production and loss rather than SOA formation.

We added this statement (Page 15, Line 27): "Isoprene oxidation is more implicated in ozone production and loss rather than SOA formation (whereas monoterpenes are more implicated in SOA formation)."

36. L8-9 - Please comment on the possible reasons for the observed enhancements over the ocean.

This explanation was originally provided later in the paper, but we have now moved it to this location.

37. L7-20 - The authors present and discuss only annual average surface concentrations. This masks seasonal changes in magnitude, sign and distribution. For example, Ashworth et al reported different patterns of ozone and SOA changes depending on wind direction between the two monsoon wind periods. And given the NOx-sensitivity of the region, the relative position of NOx and VOC sources can become even more important at different times depending on wind speed and direction. This is likely to become increasingly important as the region continues to industrialise and oil palm plantations continue to expand into areas that are currently urban / industrial rather than remote. Please discuss these limitations in the study.

The reviewer's comments would be more relevant to a surface air quality study rather than a study focused on global radiative forcing. The global mean annual average radiative forcing metric is used because it is a linear predictor of global mean surface air temperature response at steady state. Therefore, we focus on annual average analyses in this study (e.g. IPCC AR5, Myhre et al., 2013). Global and regional radiative forcing effects of perturbations to short-lived precursor emissions are typically reported on an annual-mean basis. The paper is already getting rather too long and therefore we do not include seasonal surface changes in the manuscript.

The PhD thesis "Forcings and feedbacks in the climate system: The role of reactive compounds in the atmosphere, Yale University, K. L. Harper, 2018" reports seasonal changes: "Surface ozone reductions are simulated over Peninsular Malaysia, Sumatra, and Borneo in all seasons for ΔLC (Figure 3.12). The changes in circulation and precipitation associated with the boreal winter (DJF) and boreal summer (JJA) monsoons are the likely sources of the small seasonal variations in the distribution of the surface ozone changes. The location of peak ozone enhancement over the marine environment shifts from west of Sumatra (in DJF and MAM) to north of Borneo (in JJA). Negligible changes are simulated over New Guinea in all seasons."

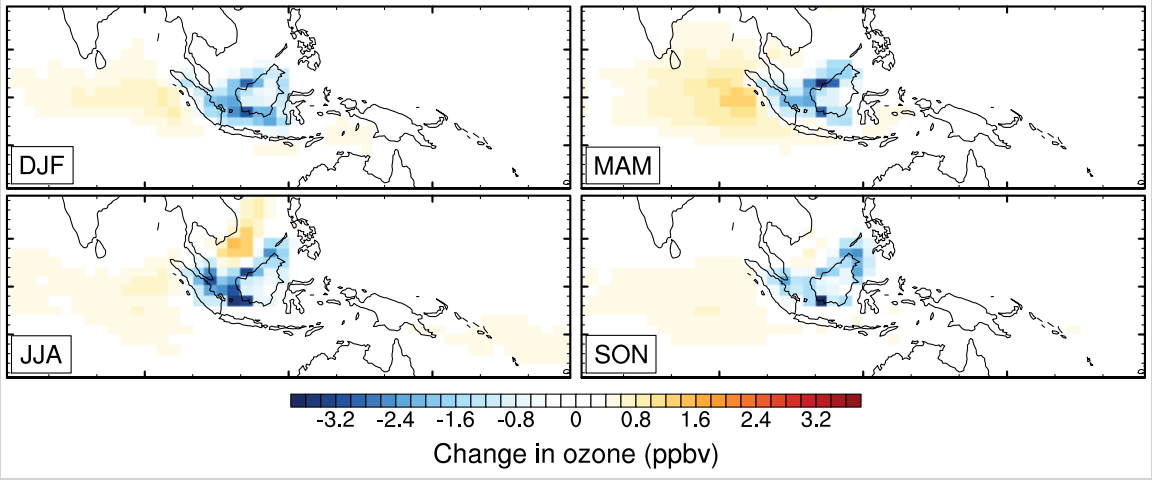

Figure 3.12. Changes in seasonal-average surface ozone mixing ratios (ppbv) for ΔLC.

38. L16-19 - What is the resolution of the NOx emissions input? As previously noted I do have concerns over the capability of the model to resolve the heterogeneity of this region and Hewitt et al. 2010 demonstrated the sensitivity of the atmospheric chemistry in this region to NOx levels over a range of BVOC emissions

The emissions input resolution corresponds to the global model resolution. See response to Point (23). Hewitt et al. (2010) used a box model. We have reservations about using a box model to simulate regional ozone air quality changes. Box models are appropriate tools to use to understand reactive radicals unaffected by transport processes and can be assumed to be in steady state in the atmosphere. Ozone has a relatively long lifetime and is strongly determined by transport and physical processes in the atmosphere. Using a box model designed to understand radical reaction pathways and kinetics to project changes in regional ozone surface air quality is just plain wrong. One may obtain some insights into key reaction pathways and important chemical species, but the projected changes in ozone concentrations aren't particularly useful in the absence of atmospheric physics and transport.

39. L28 - Please re-phrase; "inflated" sounds as if the authors applied an arbitrary increase whereas in both cases the scenarios in which NOx emissions were increased were based on the differences observed between forest and plantation.

We have re-phrased this sentence (Page 16, Line 16): "Both studies found that increasing the NO_X emissions in the region of land conversion (to account for enhanced fertilizer application and industrial processing of the oil palm) enhanced surface ozone concentrations (Ashworth et al., 2012; Warwick et al., 2013)."

Our extended introduction (which is detailed in our response to comment 1 for reviewer #3) also mentions the reason for the enhanced NO_X emissions in these studies.

As a point of clarification, the increased NO_X emissions in the Warwick et al. (2013) and Ashworth et al. (2012) studies were not entirely based on the observed differences between forest and plantation. In both studies, they increase NO_X emissions to represent increased fertilizer application of the oil palm (it appears that this is based on the observations), but they also include emissions based on increased industrial processing and, in the case of the Warwick et al. (2013) study, transportation. The transportation and processing emissions are based on estimates of energy requirements for these activities. In the Warwick et al. (2013) study, in the simulation where they apply enhanced NO_X emissions in the oil palm landscape, the applied NO_X emissions are more than 3.5x those inferred by Hewitt et al. (2009) for the oil palm landscape (0.07 mg(N) m^{-2} h^{-1} in their simulation vs. 0.019 mg(N) m^{-2} h^{-1} from the Hewitt et al. (2009) study). Hewitt et al. (2009) inferred fluxes for the forest landscape of 0.009 mg(N) m^{-2} h^{-1}, indicating that the NO_X fluxes were only about 2x as high for oil palm relative to forest. Warwick et al. (2013) apply a factor of 7 increase in NO_X emissions relative to their baseline case.

40. L34 - A likely key difference between the work of Silva and that presented here is that Silva applied the GEOS-Chem model at a resolution of 0.5deg x 0.667deg, a far more appropriate resolution for this highly complex region.

Perhaps more appropriate if the goal is to quantify regional surface air quality impacts associated with regional oil palm expansion. Again, that is not our goal here. Our study is not a regional air quality study, rather, we quantify the global radiative perturbation associated with atmospheric composition changes. As such, we apply a model with the typical resolution used by IPCC CMIP6 and HTAP for studying the global radiative impacts of regional perturbations to the short-lived precursor emissions. See response to point (8). The reviewer may consider that simply increasing horizontal resolution without changing the model's sub-grid parameterizations, processes and mechanisms does not imply an improvement in simulation accuracy. The reviewer seems to assume an automatic increase in accuracy. It depends on the linearity of the processes and impacts involved. For example, in the NOx-limited regime, ozone production has a linear dependence on NOx concentrations (Introduction to Atmospheric Chemistry, Daniel J. Jacob). Therefore, the coarse resolution grid is simply an average of the higher resolution version. Certainly, increased resolution does give more output information because the grid cell numbers have increased and that is important for regional air quality applications. GEOS-Chem is an excellent model to study regional air quality and large-scale composition changes at all the horizontal resolutions at which is it available.

Reference:
Jacob, D.J.: Introduction to Atmospheric Chemistry, Princeton University Press, 1999.

41. p11 L1-3 - But how does deposition change in YIBs which unlike GEOS-Chem couples the atmosphere to a process-based parameterisation of stomatal conductance? Otherwise I'm not sure what point the authors are trying to make here

We have updated this description (Page 16, Line 25): "The simulated changes in atmospheric composition might be a response not only to altered isoprene and monoterpene emissions, but also to changes in the deposition of atmospheric species induced by changes in leaf density (Wong et al., 2018) or related changes, such as surface roughness, stomatal conductance, and evapotranspiration, that are affected by the applied changes in land cover distribution. Here, the relative changes in regional ozone deposition rates (-19.7 to +4.3%) are similar to the relative changes in regional surface-level ozone concentrations (-18.3 to +4.3%) from 1990–2010 regional land cover change, in part because the ozone deposition rate depends on the atmospheric concentration change. While increased isoprene emission leading to increased isoprene ozonolysis drives ozone losses near the surface, a formal quantitative attribution analysis disentangling the relative roles of emission and deposition changes requires further complex sensitivity simulations that are beyond the scope of this analysis. In their analysis of Southeast Asian oil palm expansion, Silva et al. (2016) used sensitivity studies to determine that the induced BVOC emission changes, rather than altered deposition rates from LAI changes, were almost exclusively responsible for the simulated surface ozone changes."

The sentences are simply describing that isoprene oxidation under low NOx conditions leads to ozone loss (by direct reaction). That is the dominant effect determining the ozone reductions near the surface in the large-scale models.

Added reference:

Wong, A.Y.H., Tai, A.P.K., and Ip, Y.-Y.: Attribution and statistical parameterization of the sensitivity of surface ozone to changes in leaf area index based on a chemical transport model, J. Geophys. Res.-Atmos., 123, 1883–1898, doi: 10.1002/2017JD027311, 2018.

(42) Figure 1 - Please add a panel showing clearly where the changes in land cover were made. In the SI the figures imply that the changes were made only to the islands of SE Asia; here panel (a) shows a wider SE Asia than this. I suggest it would be useful for the authors to add a bounding box in each of (a) to (c) to show where the LCC occurred. I also suggest that panels should be added to show typical absolute concentrations (perhaps best done with 2010 base) of O3, SOA, isoprene and monoterpene emissions and changes in these emissions.

Figure S2 (previously known as Figure S1) shows clearly where the land cover changes were made (also see new Figure S1). We also describe in the text (Page 8, Line 14) that the land cover classification that is applied encompasses Papua New Guinea, Malaysia (Peninsular Malaysia, Sabah, and Sarawak), and three regions of Indonesia (Kalimantan, Papua, and Sumatra). In Figure 1, we show a wider region than this because we are interested in the surface ozone changes in the broader region of Southeast Asia (i.e., not only where the land cover changes occur).

In the Supplement, we show a number of plots for the 2010 base case, including Figure S3 and Figure S4. We reference these plots at relevant places in the text.

43. P12 L3–5 These 2 sentences appear to be saying the same thing; are both needed?

We agree that these two sentences are closely related, but we have retained both as they are describing slightly different things and refer to different panels of Figure 1: (1) the change in the horizontal distribution of ozone with decreasing atmospheric pressure (Figure 1c) and (2) the change in the global-mean ozone enhancement with decreasing pressure (Figure 1d).

44. L5-6 - Please state the heights/pressures being used define upper and lower troposphere; as evident from Figure 1 (d) the reported average changes in ozone will be critically dependent on this boundary.

We have added this information to this sentence (Page 18, Line 9): "Considering the troposphere, the global-mean ozone enhancement from regional land cover change is on the order of 0.5 ppbv in the upper troposphere (e.g., at 237 hPa), compared to < 0.1 ppbv in the lower troposphere (at pressures > 875 hPa)."

45. L6-7 - This seems somewhat negligible (?)

Yes.

46. L19-21 - Would suggest that the authors re-order this sentence to aid readability; the previous sentence considered isoprene so would be more logical to start with isoprene here: e.g. "When transport-driven isoprene . . ."

Fixed.

47. L26 - "-5N"? Please use "5S" for consistency with Figure 2.

Fixed.

48. L28 - Wolfe et al seems an odd choice of primary reference for the formation of HCHO from isoprene as HCHO columns have been used as a proxy since Palmer et al. 2001, 2006 and several authors since (including Palmer et al 2003) have considered the relative contributions of other VOCs to HCHO which seems of real relevance here as this study considers monoterpenes as well as isoprene, although as previously commented the text seems rather skewed toward isoprene.

We disagree. We prefer to keep the Wolfe et al. (2016) reference here because it is an important and insightful analysis based on USA field measurement data characterizing the HCHO-isoprene relationship under different NOx. There is no need to start talking about satellite HCHO columns as a proxy for isoprene emission here at this point in the paper; it would be a distraction. However, a really interesting future study could examine long-term changes in HCHO columns in the MSEA region along with satellite NOx.

49. p13 Figure 2 - Why are monoterpenes and SOA not included here? As previously noted, monoterpene emission changes and atmospheric composition impacts are barely covered.

Please see response to point (5) above. In the revised manuscript we discuss the monoterpenes and SOA more upfront in the manuscript.

We discuss the land-cover-change-driven monoterpene emissions changes in Sect. 3.1, and these are plotted in Figure S3. Regional changes in surface SOA are plotted in Figure S6.

We now state the change in the global SOA burden (Page 20, Line 32): "The global ozone perturbation induced a positive forcing of +9.2 ± 0.7 mW m^{-2}, offset only slightly by a negative forcing (-0.8 ± 0.1 mW m^{-2}) induced by a 1.4% enhancement (+6.5 Gg) in the global burden of largely reflective SOA particles. (The regional change in SOA is plotted in Figure S6.)"

The simulated global annual-mean burden of biogenic SOA is 0.46 Tg in the 2010 base simulation (2010land_base). A recent study using the UKCA model calculates the annual-mean SOA burden, considering isoprene and monoterpene precursors, as 0.41 Tg (Kelly et al., ACP 2018). In the MSEA region (here, the region shown in Figure 1a), the maximum surface SOA concentration in 4.1 μg m^{-3}, occurring over central Sumatra, with most grid cells showing concentrations of < 2 μg m^{-3}. Previous global model simulations have reported SOA concentrations of the same order of magnitude in this region (Hoyle et al., 2007; Yu, 2011). Yu (2011) simulated regional SOA concentrations of < 2 μg m^{-3}, similar to the results of the 2010land_base simulation.

References:

Hoyle, C.R., Berntsen, T., Myhre, G., and Isaksen, I.S.A.: Secondary organic aerosol in the global aerosol–chemical transport model Oslo CTM2, Atmos. Chem. Phys., 7, 5675–5694, doi: 10.5194/acp-7-5675-2007, 2007.

Kelly, J.M., Doherty, R.M., O'Connor, F., and Mann, G.W.: The impact of biogenic, anthropogenic, and biomass burning volatile organic compound emissions on regional and seasonal variations in secondary organic aerosol, Atmos. Chem. Phys., 18, 7393–7422, doi: 10.5194/acp-18-7393-2018, 2018.

Yu, F.: A secondary organic aerosol formation model considering successive oxidation aging and kinetic condensation of organic compounds: Global scale implications, Atmos. Chem. Phys., 11, 1083–1099, doi: 10.5194/acp-11-1083-2011, 2011.

50. L10-11 - but atmospheric concentrations of CO are of the order of 60-120 so this is a small relative change.

Yes.

51. L17-19 - Previously the authors have strongly made the case that this region is low-NOx. What is the yield of alkyl nitrates in ModelE2-YIBs from BVOC oxidation under low-NOx conditions as this seems more pertinent than commenting on yields in high- nix environments?

Fixed. This is a typo error. We have modified the sentence to: "In OH-initiated oxidation of isoprene in the presence of NOx,…."

52. p14 L8-9 - Although there is a clear mis-match between the spatial distribution of the enhancement in nitrates and reduction in NOx concentrations. And in particular, the formation of alkyl nitrates appears particularly increased at the surface where no change in NOx is evident. Could the authors comment on the reason for this?

We decided to show changes in concentrations in this plot in recognizable commonly used units, rather than fractional percentage changes. There are large differences in absolute concentrations between the different species in this plot. The NOx does decrease near the surface corresponding the isoprene-induced alkyl nitrate formation, but it does not show up on the plot because the absolute changes are so small on this color bar (relative to the changes in the upper troposphere).

53. L11-15 - However, unless the authors have incorporated the "new" isoprene oxidation pathways under low-NOx conditions in the chemistry mechanism (in which case this needs to be made clear in the model description section) this is more a model artefact reflecting the atmospheric chemistry community's understanding of HOx chemistry in 1999. Please clarify the isoprene oxidation scheme in ModelE2-YIBs. Is it really still CBM-4?

Defunct. No, it is not. Please see comment in top of document at response to point (9).

54. L18-19 - Again the issue of BVOC or isoprene or isoprene+monoterpenes; which is being considered here?

We altered about 20 places in the text where we previously used the term "BVOCs," now providing more specificity regarding which BVOCs are considered in the statements.

55. L22-23 - Please justify why the model is being driven with a single (repeated) year of meteorology. While it is useful to know the uncertainties associated with internal model variability it would be of far more use to know how inter-annual variability in climate / meteorology affects the radiative forcings calculated here as ultimately what is of real interest is how future LCC in the region might play out.

Addressed in point (20).

56. L23-24 - Now we come back to one of my chief concerns with the manuscript itself. This is now the first mention of aerosol changes. Although the abstract and introduction mentioned SOA as well as ozone the changes in SOA were not presented or discussed anywhere in the results section. If the authors wish to include the effects of aerosol on radiative forcing it is essential that the changes in tropospheric aerosol concentrations are introduced and discussed prior to this; likewise monoterpenes. Is the authors' reluctance to fully consider monoterpenes and SOA due to deficiencies in the chemistry mechanism and/or gas-to-particle partitioning in the ModelE2-YIBs model?

Defunct. Please see responses to point (5) and point (49). No, the initial "reluctance" to devote large sections of text in the manuscript is because the regional monoterpene emissions change and global radiative impacts from SOA are tiny, especially compared to the isoprene and ozone changes. Furthermore, as the reviewer states, understanding of SOA production mechanisms is rapidly changing and associated with large uncertainties. The global SOA modeling community has concerns about the validity of the 2-product scheme (e.g., Tsigaridis et al., 2014). Many recently published global SOA model studies in the high impact magazines use fixed yield approaches to SOA production (i.e., the original 1990s approach), for example: Rap et al., Nature Geoscience, 2018; Scott et al., Faraday Discussions, 2017; Scott et al., Nature Geoscience, 2017; Scott et al., Nature Communications, 2018. To address this issue, we have added a new uncertainty analysis in the Conclusions section based on fixed yields for SOA (Page 25, Line 10): "Our study has several limitations. The radiative forcing results are likely sensitive to the isoprene chemical mechanism, SOA production scheme, and convective transport and atmospheric transport schemes in the model. For example, this study applies the two-product scheme for SOA production (Tsigaridis and Kanakidou, 2007), but the appropriateness of using such schemes in global models is still under debate (e.g., Tsigaridis et al., 2014). Many recent global SOA model studies use fixed SOA yields for calculating SOA production from isoprene and monoterpene oxidation (e.g., Rap et al., 2018; Scott et al., 2017, 2018). For the ΔLC analysis, the global-mean SOA radiative forcing per unit of SOA burden change is -115 mW m^{-2} Tg^{-1}. This value is largely consistent across the sensitivity analyses, ranging from -112 mW m^{-2} Tg^{-1} to -119 mW m^{-2} Tg^{-1}. This metric can be used to estimate the SOA radiative forcing induced by the simulated isoprene and monoterpene emission changes under the assumption of fixed SOA yields. Assuming fixed SOA yields of 10% from the simulated monoterpene emission changes (e.g., Tsigaridis et al., 2014) and 1% from the simulated isoprene emission changes (lower end of range suggested by Kroll et al., 2005), in conjunction with the SOA forcing per burden metric, results in an SOA forcing of -2.5 mW m^{-2} from 1990–2010 land cover change

(i.e., ΔLC analysis). The SOA radiative forcing based on fixed SOA yields is more than three times stronger than, but of the same sign as, the SOA radiative forcing calculated by the global model; in both cases, the SOA radiative forcing is negligible and partially offsets the positive forcing from ozone. For the ΔLC analysis, the cumulative radiative forcing, considering impacts of both ozone and SOA changes, is 8.4 mW m^{-2} computed by the model and 6.7 mW m^{-2} computed using the simulated ozone forcing plus the SOA forcing computed here using fixed SOA yields. That is, using fixed SOA yields, the total radiative forcing would be slightly smaller in magnitude than, but the same sign as, the forcing simulated by the model. Several recent studies have applied slightly larger SOA yields: +14.3% from monoterpenes and +3.3% from isoprene (by mass; Rap et al., 2018; Scott et al., 2017, 2018). Using these larger SOA yields for the ΔLC analysis results in an SOA forcing of -19.4 mW m^{-2} and a total radiative forcing, taking into account the ozone forcing, of -10.2 mW m^{-2}, which is the opposite sign of that simulated by the model (+8.4 mW m^{-2}). This analysis indicates that uncertainty associated with biogenic SOA yields from isoprene and monoterpene oxidation has a strong influence on the quantified forcing."

We then added to the abstract (Page 1, Line 18): "The sign of the net forcing is sensitive to uncertainty in the SOA yield from BVOCs."

References:

Kroll, J.H., Ng, N.L., Murphy, S.M., Flagan, R.C., and Seinfeld, J.H.: Secondary organic aerosol formation from isoprene photooxidation under high-NO_X conditions, Geophys. Res. Lett., 32, L18808, doi: 10.1029/2005GL023637, 2005.

Rap, A., Scott, C.E., Reddington, C.L., Mercado, L., Ellis, R.J., Garraway, S., Evans, M.J., Beerling, D.J., MacKenzie, A.R., Hewitt, C.N., and Spracklen, D.V.: Enhanced global primary production by biogenic aerosol via diffuse radiation fertilization, Nat. Geosci., et al., Nat Geoscience, doi: 10.1038/s41561-018-0208-3, 2018.

Scott, C.E., Arnold, S.R., Monks, S.A., Asmi, A., Paasonen, P., and Spracklen, D.V.: Substantial large-scale feedbacks between natural aerosols and climate, Nat Geoscience, 11, 44–48, doi: 10.1038/s41561-017-0020-5, 2018.

Scott, C.E., Monks, S.A., Spracklen, D.V., Arnold, S.R., Forster, P.M., Rap, A., Äijälä, M., Artaxo, P., Carslaw, K.S., Chipperfield, M.P., Ehn, M., Gilardoni, S., Heikkinen, L., Kulmala, M., Petäjä, T., Reddington, C.L.S., Rizzo, L.V., Swietlicki, E., Vignati, E., and Wilson, C.: Impact on short-lived climate forcers increases projected warming due to deforestation, Nat. Commun., 9:157, 1–9, doi: 10.1038/s41467-017-02412-4, 2018.

Scott, C.E., Monks, S.A., Spracklen, D.V., Arnold, S.R., Forster, P.M., Rap, A., Carslaw, K.S., Chipperfield, M.P., Reddington, C.L.S., and Wilson, C.: Impact on short-lived climate forcers

(SLCFs) from a realistic land-use change scenario via changes in biogenic emissions, Faraday Discuss., 200, 101–120, doi: 10.1039/c7fd00028f, 2017.

Tsigaridis, K., Daskalakis, N., Kanakidou, M., Adams, P.J., Artaxo, P., Bahadur, R., Balkanski, Y., Bauer, S.E., Bellouin, N., Benedetti, A., Bergman, T., Berntsen, T.K., Beukes, J.P., Bian, H., Carslaw, K.S., Chin, M., Curci, G., Diehl, T., Easter, R.C., Ghan, S.J., Gong, S.L., Hodzic, A., Hoyle, C.R., Iversen, T., Jathar, S., Jimenez, J.L., Kaiser, J.W., Kirkevåg, A., Koch, D., Kokkola, H., Lee, Y.H., Lin, G., Liu, X., Luo, G., Ma, X., Mann, G.W., Mihalopoulos, N., Morcrette, J.-J., Müller, J.-F., Myhre, G., Myriokefalitakis, S., Ng, N.L., O'Donnell, D., Penner, J.E., Pozzoli, L., Pringle, K.J., Russell, L.M., Schulz, M., Sciare, J., Seland, Ø., Shindell, D.T., Sillman, S., Skeie, R. B., Spracklen, D., Stavrakou, T., Steenrod, S.D., Takemura, T., Tiitta, P.,Tilmes, S., Tost, H., van Noije, T., van Zyl, P.G., von Salzen, K., Yu, F., Wang, Z., Wang, Z., Zaveri, R. A., Zhang, H., Zhang, K., Zhang, Q., and Zhang, X.: The AeroCom evaluation and intercomparison of organic aerosol in global models, Atmos. Chem. Phys, 14, 10845–10895, doi: 10.5194/acp-14-10845-2014, 2014.

57. L27-30 - Given the levels of uncertainty in calculations of radiative forcing, and the limitations previously identified with this study, it is hard to see a net forcing of 0.008 Wm-2 as globally significant. The more substantial (but highly localised changes over the Indian Ocean) could be of real interest in terms of how they affect the Indian monsoon which has seen significant changes in recent years, but this is not explored by the authors. Again, however, these are temporally "averaged" results whereas the "interesting" effects are likely to be temporally as well as spatially localised. This would be another extremely interesting avenue to explore. Do the changes peak at times and locations when small changes in climate-relevant atmospheric components matter?

The reviewer misuses the term "significant" above. We do provide uncertainty estimate for the net global climate impact (+8.4 ± 0.7 mW m^{-2}). We have rebutted the reviewer's previous concerns and misunderstandings (please see all comments above). We agree with the reviewer that the global ozone radiative forcing from the oil palm expansion in MSEA is small. That is the main finding of this study and stated several times in the Conclusions section. We did not know before we launched the experiments what would be the final results.

In the Conclusions section we have added (Page24, Line 17): "For comparison, the global ozone forcing driven by the 1990–2010 land cover change in MSEA is at the low end of the range of estimates for ozone forcing from global anthropogenic emission source sectors in year 2000 (+5 to +80 mW m^{-2}): for example, industry = +15 mW m^{-2}; household biofuel +28 mW m^{-2}; road transport = +50 mW m^{-2}; power = +53 mW m^{-2}; biomass burning +71 mW m^{-2} (Fuglestvedt et al., 2008; Unger et al., 2010). A multi-model study found that 20% reductions in NMVOCs (about 2–4 TgC y^{-1}) in four large world regions (North America, East Asia, Europe, and South Asia) in 2001 led to global ozone forcings around -1 mW m^{-2} (Fry et al., 2012)."

The review raises some interesting new ideas about the regional radiative impacts. Regional forcing and regional climate response are not correlated. Regional climate change is not well understood, and the regional climate response to regional aerosol emissions is currently model-dependent. Examining the regional climatic response to regionalized forcing over the Indian Ocean would require at the least a full-time PhD project, and also coordinated experiments in several fully coupled global climate model runs to assess the robustness of the responses. Our study provides a quantitative spatial map of the annual-mean ozone forcing due to 1990–2010 maritime Southeast Asian land cover change (Figure 3).

Reference:

Fry, M.M., Naik, V., West, J.J., Schwarzkopf, M.D., Fiore, A.M., Collins, W.J., Dentener, F.J., Shindell, D.T., Atherton, C., Bergmann, D., Duncan, B.N., Hess, P., MacKenzie, I.A., Marmer,E., Schultz, M.G., Szopa, S., Wild, O., and Zeng, G.: The influence of ozone precursor emissions from four world regions on tropospheric composition and radiative climate forcing, J. Geophys. Res., 117, D07306, doi: 10.1029/2011JD017134, 2012.

Fuglestvedt, J., Berntsen, T., Myhre, G., Rypdal, K., and Skeie, R.B.: Climate forcing from the transport sectors, P. Natl. Acad. Sci. USA, 105, 454–458, doi: 10.1073/pnas.0702958104, 2008.

Unger, N., Bond, T.C., Wang, J.S., Koch, D.M., Menon, S., Shindell, D.T., and Bauer, S.: Attribution of climate forcing to economic sectors, P. Natl. Acad. Sci. USA, 107, 3382–3387, doi: 10.1073/pnas.0906548107, 2010.

58. p16 L1-2 - See previous comments regarding monoterpene and SOA results and discussions. But interesting to note that O3 and SOA forcings seem to scale, presumably also with isoprene emissions changes. But this comes back to my previous questions regarding the fitness of the chemistry mechanism for the conditions encountered in this region and the ability of the model to capture the heterogeneity of land and chemical climatology given its coarse resolution.

See responses to comments (8) and (9). Please see response to points (5), (49), (55). Comment is now defunct. The climate policy metrics (ozone global radiative forcing per Mha oil palm conversion in tropics) are an innovation of this study. For example, they can be used to assess quickly the global climate impacts of future projections in land cover change and scenarios in the tropics.

59. L16-18 - See previous questions and comments regarding inter-annual variability; as noted by the authors in L10-12 the isoprene flux is critically dependent on meteorology and so presumably the impact on radiative forcing would be similarly sensitive.

Please see response to point (20).

60. L20-32 - I do not understand why the authors chose a x12 enhancement in isoprene emission factor from the dipterocarp forest given the x3 enhancement observed during in-situ measurements. Further, given the incredibly low isoprene emissions from these forests relative to both other natural tropical ecosystems and oil palm plantations why there was a need for this sensitivity test. Monoterpene emissions are relatively strong from dipterocarp forests so I would have expected to see a sensitivity test involving increased monoterpene emission rates instead. Perhaps the authors could comment on why this was not done?

The sensitivity test reflects the difference between the observed leaf-level isoprene BER for dipterocarp forest tree species and the leaf-level isoprene BER used for the standard tropical forest PFT in YIBs. The analysis is designed to test the sensitivity of the forcing to uncertainty in the assigned forest isoprene BER. Other studies have also shown that the standard isoprene emission capacity in MEGAN for Southeast Asian forests was likely overestimated (e.g., Stavrakou et al., 2014).

61. p17 L2-4 - However, this forest loss is likely to have affected monoterpene emissions more substantially, coming back to my previous questions regarding the importance of monoterpenes and SOA contributions to the LCC-induced radiative forcing in the region and whether this is well captured in the model used.

We have extended our analysis of uncertainty in the SOA formation scheme by adding new analysis in the Conclusions, as described in point (56).

62. L6-9 - Here and in many other sections of the discussion section I feel that the authors have lost objectivity and are attempting to over-emphasise aspects of their results to fit a particular narrative. The study covers a 20-year period. If the annual changes were constant you would expect to see 75% of the forcing associated with 1990-2005; 69% is not so far from that. As the authors have only broken the 20-year period down in one way rather than into 5-year blocks throughout they do not have sufficient evidence that the 5-year period from 2005-2010 is worse than every other 5-year period which would be needed to support the statement that the forcing is "rapidly increasing".

We retained this sentence (Page 23, Line 6): "The total forcing associated with 1990–2005 land cover change (ΔLC-2005) is 69% of the forcing associated with 1990–2010 land cover change (ΔLC), indicating that 31 % of the total 1990–2010 forcing is associated with land cover change that occurred over the short 2005–2010 period."

We removed this sentence: "This sensitivity study demonstrates that the climate forcing associated with regional land cover change is rapidly increasing."

63. L19-22 - Presumably this underestimation is likely to affect both the 1990 and 2010 land cover maps. Have the authors attempted to find out from other sources (e.g. FOA, Malaysian Oil Palm Board, Round Table for Sustainable Palm Oil) whether the proportion of smallholder

plantings to industrial plantations has remained constant during the rapid expansion of the oil palm industry or whether the number of smallholder plantings has remained closer to the 1990 figures?

The underestimation affects both the 1990 and 2010 oil palm areal cover. We apply the 40% figure for underestimation to all regions for both 1990 and 2010; that is, we estimate that the oil palm areal cover in our land cover dataset (derived from the Gunarso et al. (2013) dataset) accounts for 60% of the total on-the-ground areal cover in Indonesia, Malaysia, and Papua New Guinea in both 1990 and 2010. As far as we can tell, estimates for 1990 in Malaysia are not readily available; however, the Malaysian Palm Oil Board (MPOB) reports this figure as about 40% for 2004 (Vermeulen and Goad, 2006, citing MPOB) and about 40% for 2014–2016 (MPOB). The Indonesian Ministry of Agriculture reports this figure as 26% for 1990 and 40% for 2010 (Indonesian Ministry of Agriculture, 2017).

Application of the 26% smallholder figure for Indonesia in 1990 (in place of the 40% figure) does not change the estimated forcing that takes into account the smallholder area (+16 mW m^{-2}). The ozone forcing estimate that includes the smallholder area is insensitive to small changes in the smallholder fraction (i.e., 26% or 40%) because Indonesian oil palm cover in 1990 was only about 1.3 Mha. It is unknown what proportion of the smallholder area (both schemed and independent) is included in the oil palm areal cover classified by the Gunarso et al. (2013) methodology. Thus, we consider this estimate to be an upper bound on the ozone forcing (Page 23, Line 30).

We have updated the manuscript to reflect these additional references (Page X, Line X): "Estimates suggest that around 40% of Indonesian oil palm area in 2010 (and 26% in 1990) was associated with smallholders, in contrast to state-owned or private companies (Indonesian Ministry of Agriculture, 2017; Lee et al., 2014). In Malaysia, the smallholder estimate is likewise around 40% (Vermeulen and Goad, 2006, citing the Malaysian Palm Oil Board)."

References:

Indonesian Ministry of Agriculture: Tree Crop Estate Statistics of Indonesia 2015–2017, Directorate General of Estate Crops, Ministry of Agriculture, Indonesia, 2017.

Malaysian Palm Oil Board (MPOB), Economics and Industry Development Division, Statistics: bepi.mpob.gov.my, accessed: 25 August 2018.

Vermeulen, S. and Goad, N.: Towards better practice in smallholder palm oil production, Natural Resource Issues Series (No. 5), International Institute for Environment and Development, London, UK, 2006.

64. L26 - Can the authors clarify what they mean by "extrapolating the smallholder estimate"? Do they mean they assume that 40% of reported oil palm area across the whole of SE Asia and through the entire time period represents smallholdings? So they assume that the area they have taken from Gunarso represents only 60% of the actual extent of oil palm cultivation? See above regarding justification of this assumption.

Also see response to point (63).

We updated the text (Page 23, Line 26): "Taking into account the smallholder estimates for Indonesia and Malaysia, the total regional expansion of oil palm cover for 1990–2010 increases to +16 Mha, which is considered to be an upper bound."

65. -34 - To what extent is this insensitivity the result of the coarse resolution and outdated chemistry scheme?

Defunct comment. See responses to points (8) and (9) above and comments at top of document.

66. p18 L5-10 - Please explain why an increase in surface ozone concentrations could not be concomitant with increases in upper tropospheric ozone?

We have removed this sentence that was badly phrased. We were originally trying to emphasize that increases in ozone near the Earth's surface do not exert appreciable longwave forcing but we agree the original sentence does not read well and is not scientifically nuanced enough.

67. L11-12 - Please could the authors attempt to list some of the uncertainties not considered by the sensitivity tests that might be expected to be substantial?

Yes. Actually, we did already highlight uncertainties in chemistry (Page 8, Line 6): "Future work would benefit from an exploration of the impact on radiative forcing induced through application of different mechanisms of (1) isoprene photooxidation and (2) SOA formation (e.g., Surratt et al., 2010; Zhang et al., 2018)." The expanded preceding paragraph, moved to the Methodologly Sect. 2.1 from the Conclusions Sect. 4, further discusses these uncertainties. We have additionally added to the Conclusions section a discussion of the uncertainty in the SOA forcing associated with the SOA production scheme applied (Page 25, Line 10; and included in response to point (56).

68. L21-22 - The authors have just stated that their best estimate is +8.4; that is therefore the figure that should be quoted here, in which case we are looking at 3.5x.

The reviewer is wrong and splitting hairs. The IPCC AR5 did not quantify SOA changes from NMVOC emissions. The IPCC AR5 does quantify ozone radiative forcing from NMVOC changes. Therefore, we compare the ozone forcing response from historical anthropogenic VOC changes as reported by IPCC AR5 (+30 mW m^{-2}; Myhre et al., 2013) to the global ozone radiative forcing from this present study (+9.2 mW m^{-2}). We posit that this is a useful ballpark comparison to put the global impacts into context for our readers especially those from the short-lived climate forcer and global chemistry–climate modeling communities.

69. L27 - As highlighted previously, the authors are over-emphasising the magnitude and implications of their findings. Using 8.4 suggests a figure of 11.5 rather than 12.7 mW m-2.

The reviewer's comment is absurd. The actual sentence states: "regional oil palm expansion over the modern era is responsible for a global-mean forcing of +12.7 mW m^{-2} from induced ozone changes." The calculation is for the ozone changes only and this cannot be more clearly stated than it is. Therefore, the calculation is based on the ozone forcing (+9.2 mW m^{-2}). All this said, the tiny difference between 11.5 mW m^{-2} and 12.7 mW m^{-2} does not in any way support the reviewer's false claim of us "over-emphasising the magnitude and implications of their findings."

70. L28-31 - It would have been of real interest if the authors had looked at future projections rather than confining the study to historical LCC and radiative forcing.

We agree that future projections are very interesting for follow-up studies. Does the reviewer mean that examining a real world case study of a large human-induced land cover change and isoprene emission perturbation that is known to have occurred in the system over the past 20 years is not interesting? We hope not. "To understand the present one must also know the past," Sir Peter Crane. In addition, we have provided climate policy metrics that can be used to assess quickly the impacts of future projections.

71. p19 L1-2 - Just out of curiosity, how much more uncertainty is associated with isoprene BERs from oil palm in comparison with isoprene emissions from other tropical species / ecosystems OR monoterpene BERs from rubber palms which the authors earlier highlight as important factors in the changes in BVOC emissions in the region.

We do not have access to the necessary sensitivity simulations to provide a quantitative answer.

72. L10-19 - Equally, many previous studies (e.g. Grate et al 2007) have shown strong apparent seasonality in BERs that are not adequately accounted for by consideration of leaf

age. Inclusion of seasonally varying BERs might also be argued as improving the estimated radiative forcing in this study.

We have included this sentence in this paragraph (Page 26, Line 1): "Seasonal variation in isoprene BERs has been observed for some tree species (e.g., Geron et al., 2000)."

Reference:
Geron, C., Guenther, A., Sharkey, T., and Arnts, R.R.: Temporal variability in basal isoprene emission factor, Tree Physiol., 20, 799–805, 2000.

73. L18-19 - The isoprene vs BVOC issue again. Presumably given the focus of the paragraph to this point the authors are referring to the isoprene BER in YIBs.

Fixed. Also see point (54).

74. L18-19 - And again, the issue of misrepresentation. In the title and throughout the manuscript the authors refer to BVOC emissions and emission changes yet YIBs includes only a very limited number of BVOCs, and here the authors have only altered isoprene and monoterpene BERs. I suggest that the authors remove the term BVOCs from the title and discussions as it is not an accurate reflection of the study performed. Likewise the authors need to devote far more attention to the changes in monoterpenes and SOA throughout the main text.

Defunct. Please see e.g. response to point (5). We retain "BVOCs" in the title as we study isoprene and monoterpene changes that are the major BVOC emissions emitted with the most important large-scale radiative effects. In about 20 instances in the text, we have updated the text to replace the term "BVOC" with more explicit descriptions of which BVOCs (isoprene and/or monoterpenes) are being discussed.

75. L21-34 - This discussion of OH recycling in the conclusions section is disturbing on a number of counts. (1) This is the first and only discussion of the apparent limitations of the chemical mechanism in ModelE2-YIBs, as previously commented above. Can the authors please describe exactly what BVOC oxidation chemistry is included in the "based on Carbon Bond Mechanism-4" scheme? As previously noted, CBM-4 was developed for high NOx anthropogenic VOC-rich urban environments and such schemes have been found to inadequately capture observed concentrations / chemistry / oxidation products in low-NOx high BVOC environments such as those in SE Asia. (2) The field of isoprene oxidation chemistry has moved on considerably since the sensitivity studies employing crude "OH-recycling" schemes referenced here with new pathways identified leading to the regeneration of HOx in low-NOx environments. (3) While surface ozone concentrations might be only negligibly affected the authors have repeatedly argued elsewhere that these are not the changes that are significant in terms of radiative forcing. (4) The new understanding of

isoprene chemistry gained in trying to reconcile the apparent differences between modeled and observed gas-phase chemistry has also identified mechanisms driving high yields of isoprene-derived SOA via MACR oxidation. The points made in this paragraph bring into question the validity of the modeled changes in ozone and SOA presented here. It also raises questions regarding the monoterpene oxidation scheme and gas-to-particle phase partitioning included.

Comment now defunct. We moved the paragraph about uncertainties in isoprene chemical mechanism into the Methods Section 2.1 (Page 7, Line 21). We have modified this paragraph to provide a more balanced assessment of these uncertainties. The mechanism is not CBM04. Please see comments at top of document and response to point (9). In this modified paragraph, we have added more analysis and discussion on the SOA uncertainty. As described in point (56), we have added a new paragraph in the Conclusions Sect. 4 discussing uncertainty related to the SOA formation scheme in the model (Page 25, Line 10).

Likewise, the fact that surface ozone air quality and ozone radiative forcing responses to small changes in precursor emission changes (including NMVOCs) are being simulated at 1–2° latitude/longitude spatial resolution using highly simplified parameterizations raises important questions about the level of chemical mechanism detail required to simulate ozone (Turnock et al., ACP, 2018; Wild et al., ACP, 2012), especially considering that the parameterizations were developed using a large number of global models all featuring very different levels of complexity in anthropogenic VOC and BVOC representation and photooxidation mechanism.

References:

Turnock, S.T., Wild, O., Dentener, F.J., Davila, Y., Emmons, L.K., Flemming, J., Folberth, G.A., Henze, D.K., Jonson, J.E., Keating, T.J., Kengo, S., Lin, M., Lund, M., Tilmes, S., and O'Connor, F.M.: The impact of future emission policies on tropospheric ozone using a parameterized approach, Atmos. Chem. Phys., 18, 8953–8978, doi: 10.5194/acp-18-8953-2018, 2018.

Wild, O., Fiore, A.M., Shindell, D.T., Doherty, R.M., Collins, W.J., Dentener, F.J., Schultz, M.G., Gong, S., MacKenzie, I.A., Zeng, G., Hess, P., Duncan, B.N., Bergmann, D.J., Szopa, S., Jonson, J.E., Keating, T.J., and Zuber, A.: Modelling future changes in surface ozone: A parameterized approach, Atmos. Chem. Phys., 12, 2037–2054, doi: 10.5194/acp-12-2037-2012, 2012.

76. p20 L1-2 - Actually this should have been included in this work as the chemistry seems to be a critical source of uncertainty that has not been adequately considered.

Formally assessing the sensitivity to different chemical mechanisms is beyond the scope of this work. A multi-model assessment of short-lived climate forcer responses to modern human land cover change (biofuel, afforestation, etc.) would be a really interesting future study.

77. L8-9 - Concluding with the absolute maximum single pixel increase is not scientifically balanced. Please maintain objectivity rather than cherry-picking the results to fit a particular narrative.

Please check your own biases and read carefully the Obligations for Referees and Code of Conduct for Copernicus Journals before agreeing to reviewer assignments (https://publications.copernicus.org/for_reviewers/obligations_for_referees.html).

We disagree with the reviewer's comment. We start and end the Conclusions section by describing how the global forcing from the short-lived climate forcers due to the 1990–2010 oil palm expansion is small. The full sentence is: "While the impact on global radiative forcing is small, the ozone radiative forcing exceeds +37 mW m^{-2} in some localities" and it is not the final sentence of the Conclusions section. Since the Reviewer in point (57) has suggested themselves that the most "interesting" effects are likely to be temporally as well as spatially localized, we retain the sentence as is. We thought hard about how to explain the meaning of the global ozone and SOA radiative forcing quantitative results from the oil palm expansion and to put it into a meaningful context that readers may connect with. We state several times in the Conclusions section that the 1990–2010 impact is small.

In the Conclusions section, we have added (Page 24, Line 17): "For comparison, the global ozone forcing driven by the 1990–2010 land cover change in MSEA is at the low end of the range of estimates for ozone forcing from global anthropogenic emission source sectors in year 2000 (+5 to +80 mW m^{-2}): for example, industry = +15 mW m^{-2}; household biofuel +28 mW m^{-2}; road transport = +50 mW m^{-2}; power = +53 mW m^{-2}; biomass burning = +71 mW m^{-2} (Fuglestvedt et al., 2008; Unger et al., 2010). A multi-model study found that 20% reductions in NMVOCs (about 2-4 TgC y^{-1}) in four large world regions (North America, East Asia, Europe, and South Asia) in 2001 led to global ozone forcings around -1mW m^{-2} (Fry et al., 2012)."

"Small" and "large" are to some extent value judgments and not purely objective. It is our job to use mathematical modeling to provide quantitative values for Earth system and global change processes involving the short-lived climate forcers. 9 mW m^{-2} or 37 mW m^{-2} is small and even negligible compared to > 1800 mW m^{-2} CO_2 global forcing. Is 9 (4–16) mW m^{-2} from a regional BVOC injection due to recent human-induced land cover change in the tropics "small" compared to 30 mW m^{-2} due to all anthropogenic VOC increases since the preindustrial; or 50 mW m^{-2} due to global road transportation emissions? Social scientists are better equipped to answer this question. We offer a perspective on the sensitivity of the tropical atmosphere to human land cover change.

References

Angiola, A., Mieville, A., and Granier, C.: MACCity (MACC/CityZEN EU projects) emissions dataset [Data files], Emissions of atmospheric Compounds & Compilation of Ancillary Data, http://eccad.sedoo.fr, 2010.

Archibald, A.T., Jenkin, M.E., Shallcross, D.E.: An isoprene mechanism intercomparison, Atmos. Environ., 44, 5356–5364, doi: 10.1016/j.atmosenv.2009.09.016, 2010.

Ashworth, K., Folberth, G., Hewitt, C.N., and Wild, O.: Impacts of near-future cultivation of biofuel feedstocks on atmospheric composition and local air quality, Atmos. Chem. Phys, 12, 919–939, doi: 10.5194/acp-12-919-2012, 2012.

Atkinson, R. and Arey, J.: Gas-phase tropospheric chemistry of biogenic volatile organic compounds: A review, Atmos. Environ., 37, S197–219, doi: 10.1016/S1352-2310(03)00391-1, 2003.

Baker, B., Bai, J.-H., Johnson, C., Cai, Z.-T., Li, Q.-J., Wang, Y.-F., Guenther, A., Greenberg, J., Klinger, L., Geron, C., and Rasmussen, R.: Wet and dry season ecosystem level fluxes of isoprene and monoterpenes from a southeast Asian secondary forest and rubber tree plantation, Atmos. Environ., 39, 381–390, doi: 10.1016/j.atmosenv.2004.07.033, 2005.

Bauer, S.E. and Koch, D.: Impact of heterogeneous sulfate formation at mineral dust surfaces on aerosol loads and radiative forcing in the Goddard Institute for Space Studies general circulation model, J. Geophys. Res., 110, D17202, doi: 10.1029/2005JD005870, 2005.

Bauer, S.E., Koch, D., Unger, N., Metzger, S.M., Shindell, D.T., and Streets, D.G.: Nitrate aerosols today and in 2030: a global simulation including aerosols and tropospheric ozone, Atmos. Chem. Phys., 7, 5043–5059, doi: 10.5194/acp-7-5043-2007, 2007a.

Bauer, S.E., Mishchenko, M.I., Lacis, A.A., Zhang, S., Perlwitz, J., and Metzger, S.M.: Do sulfate and nitrate coatings on mineral dust have important effects on radiative properties and climate modeling?, J. Geophys. Res., 112, D06307, doi: 10.1029/2005JD006977, 2007b.

Beer, C., Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., Rödenbeck, C., Arain, M.A., Baldocchi, D., Bonan, G.B., Bondeau, A., Cescatti, A., Lasslop, G., Lindroth, A., Lomas, M., Luyssaert, S., Margolis, H., Oleson, K.W., Roupsard, O., Veenendaal, E., Viovy, N., Williams, C., Woodward, F.I., and Papale, D.: Terrestrial gross carbon dioxide uptake: Global distribution and covariation with climate, Science, 329, 834–838, doi: 10.1126/science.1184984, 2010.

Bell, N., Koch, D., and Shindell, D.T.: Impacts of chemistry–aerosol coupling on tropospheric ozone and sulfate simulations in a general circulation model, J. Geophys. Res., 110, D14305, doi: 10.1029/2004JD005538, 2005.

Bian, H. and Prather, M.J.: Fast-J2: Accurate simulation of stratospheric photolysis in global chemical models, J. Atmos. Chem., 41, 281–296, doi: 10.1023/A:1014980619462, 2002.

Bian, H., Prather, M.J., and Takemura, T.: Tropospheric aerosol impacts on trace gas budgets through photolysis, J. Geophys. Res., 108, 4242, doi: 10.1029/2002JD002743, 2003.

Carlson, K.M., Curran, L.M., Asner, G.P., Pittman, A.M., Trigg, S.N., and Marion Adeney, J.: Carbon emissions from forest conversion by Kalimantan oil palm plantations, Nat. Clim. Change, 3, 283–287, doi: 10.1038/nclimate1702, 2012.

Carlson, K.M., Curran, L.M., Ratnasari, D., Pittman, A.M., Soares-Filho, B.S., Asner, G.P., Trigg, S.N., Gaveau, D.A., Lawrence, D., and Rodrigues, H.O.: Committed carbon emissions, deforestation, and community land conversion from oil palm plantations expansion in West Kalimantan, Indonesia, Proc. Natl. Acad. Sci.-USA, 109, 7559–7564, doi: 10.1073/pnas.1200452109, 2012b.

Carlton, A.G., Wiedinmyer, C., and Kroll, J.H.: A review of secondary organic aerosol (SOA) formation from isoprene, Atmos. Chem. Phys., 9, 4987–5005, doi: 10.5194/acp-9-4987-2009, 2009.

Dietz, J., Hölscher, D., Leuschner, C., Malik, A., and Amir, M.A.: Forest structure as influenced by different types of community forestry in a lower montane rainforest of Central Sulawesi, Indonesia, in: Stability of Tropical Rainforest Margins: Linking Ecological, Economic and Social Constraints of Land Use and Conservation, edited by: Tscharntke, T., Leuschner, C., Zeller, M., Guhardja, E., and Biden, A., Springer-Verlag, Berlin, pp. 131–146, 2007.

Draper, D.C., Farmer, D.K., Desyaterik, Y., and Fry, J.L.: A qualitative comparison of secondary organic aerosol yields and composition from ozonolysis of monoterpenes at varying concentrations of NO2, Atmos. Chem. Phys., 15, 12267–12281, doi: 10.5194/acp-15-12267-2015, 2015.

Emmerson, K. M. and Evans, M. J.: Comparison of tropospheric gas-phase chemistry schemes for use within global models, Atmos. Chem. Phys., 9, 1831–1845, doi: 10.5194/acp-9-1831-2009, 2009.

FAO: FAOSTAT Emissions Database [Electronic database], Food and Agriculture Organization of the United Nations, http://www.fao.org/faostat/en/#data, 2014.

Fowler, D., Nemitz, E., Misztal, P., Di Marco, C., Skiba, U., Ryder, J., Helfter, C., Cape, J.N., Owen, S., Dorsey, J., Gallagher, M.W., Coyle, M., Phillips, G., Davison, B., Langford, B., MacKenzie, R., Muller, J., Siong, J., Dari-Salisburgo, C., Di Carlo, P., Aruffo, E., Giammaria, F., Pyle, J.A., and Hewitt, C.N.: Effects of land use on surface-atmosphere exchanges of trace gases and energy in Borneo: Comparing fluxes over oil palm plantations and a rainforest, Philos. T. R. Soc. B, 366, 3196–3209, doi: 10.1098/rstb.2011.0055, 2011.

Friedman, B. and Farmer, D.K.: SOA and gas phase organic acid yields from the sequential photooxidation of seven monoterpenes, Atmos. Env., 187, 335–345, doi: 10.1016/j.atmosenv.2018.06.003, 2018.

Fry, M.M., Naik, V., West, J.J., Schwarzkopf, M.D., Fiore, A.M., Collins, W.J., Dentener, F.J., Shindell, D.T., Atherton, C., Bergmann, D., Duncan, B.N., Hess, P., MacKenzie, I.A., Marmer,E., Schultz, M.G., Szopa, S., Wild, O., and Zeng, G.: The influence of ozone precursor emissions from four world regions on tropospheric composition and radiative climate forcing, J. Geophys. Res., 117, D07306, doi: 10.1029/2011JD017134, 2012.

Fuglestvedt, J., Berntsen, T., Myhre, G., Rypdal, K., and Skeie, R.B.: Climate forcing from the transport sectors, P. Natl. Acad. Sci. USA, 105, 454–458, doi: 10.1073/pnas.0702958104, 2008.

Gaveau, D.L.A., Salim, M.A., Hergoualc'h, K., Locatelli, B., Sloan, S., Wooster, M., Marlier, M.E., Molidena, E., Yaen, H., DeFries, R., Verchot, L., Murdiyarso, D., Nasi, R., Holmgren, P., and Sheil, D.: Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: Evidence from the 2013 Sumatran fires, Sci. Rep.-U.K., 4, 6112, doi: 10.1038/srep06112, 2014.

Geron, C., Guenther, A., Sharkey, T., and Arnts, R.R.: Temporal variability in basal isoprene emission factor, Tree Physiol., 20, 799–805, 2000.

Geron, C., Owen, S., Guenther, A., Greenberg, J., Rasmussen, R., Bai, J.H., Li, Q.-J., and Baker, B.: Volatile organic compounds from vegetation in southern Yunnan Province, China: Emission rates and some potential regional implications, Atmos. Environ., 40, 1759–1773, doi: 10.1016/j.atmosenv.2005.11.022, 2006.

Gery, M.W., Whitten, G.Z., Killus, J.P., and Dodge, M.C.: A photochemical kinetics mechanism for urban and regional scale computer modeling, J. Geophys. Res.-Atmos., 94, 12,925–12,956, doi: 10.1029/JD094iD10p12925, 1989.

Granier, C., Bessagnet, B., Bond, T., D'Angiola, A., Denier van der Gon, H., Frost, G.J., Heil, A., Kaiser, J.W., Kinne, S., Klimont, Z., Kloster, S., Lamarque, J.-F., Liousse, C., Masui, T., Meleux, F., Mieville, A., Ohara, T., Raut, J.-C., Riahi, K., Schultz, M.G., Smith, S.J., Thompson, A., van Aardenne, J., van der Werf, G.R., and van Vuuren, D.P.: Evolution of anthropogenic and biomass burning emissions of air pollutants at global and regional scales during the 1980–2010 period, Climatic Change, 109, 163–190, doi: 10.1007/s10584-011-0154-1, 2011.

Guenther, A., Hewitt, C.N., Erickson, D., Fall, R., Geron, C., Graedel, T., Harley, P., Klinger, L., Lerdau, M., McKay, W.A., Pierce, T., Scholes, B., Steinbrecher, R., Tallamraju, R., Taylor, J., and Zimmerman, P.: A global model of natural volatile organic compound emissions, J. Geophys. Res.-Atmos., 100, 8873–8892, doi: 10.1029/94JD02950, 1995.

Guenther, A.B., Jiang, X., Heald, C.L., Sakulyanontvittaya, T., Duhl, T., Emmons, L.K., and Wang, X.: The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1): An extended and updated framework for modeling biogenic emissions, Geosci. Model Dev., 5, 1471–1492, doi: 10.5194/gmd-5-1471-2012, 2012.

Gunarso, P., Hartoyo, M.E., Agus, F., and Killeen, T.J.: Oil palm and land use change in Indonesia, Malaysia, and Papua New Guinea: Reports from the Technical Panels of the 2nd Greenhouse Gas Working Group of the Roundtable on Sustainable Palm Oil (RSPO), Roundtable on Sustainable Palm Oil, Kuala Lumpur, Malaysia, 2013.

Hallquist, M., Stewart, D.J., Stephenson, S.K., and Cox, R.A.: Hydrolysis of N_2O_5 on sub-micron sulfate aerosols, Phys. Chem. Chem. Phys., 5, 3453–3463, doi: 10.1039/b301827j, 2003.

Hanson, D. and Mauersberger, K.: Laboratory studies of the nitric acid trihydrate: Implications for the south polar stratosphere, Geophys. Res. Lett., 15, 855–858, doi: 10.1029/GL015i008p00855, 1988.

Harper, K.L., Zheng, Y., and Unger, N.: Advances in representing interactive methane in ModelE2-YIBs (version 1.1), Geosci. Model Dev. Discuss., doi: 10.5194/gmd-2018-85 , 2018.

Heald, C.L. and Geddes, J.A.: The impact of historical land use change from 1850 to 2000 on secondary particulate matter and ozone, Atmos. Chem. Phys., 16, 14997–15010, doi: 10.5194/acp-16-14997-2016, 2016.

Heil, A. and Schultz, M.G.: Interpolated ACCMIP and RCP emission dataset [Data files], Available from: http://accmip-emis.iek.fz-juelich.de/data/accmip/gridded_netcdf/accmip_interpolated/, 2014.

Hewitt, C.N., Lee, J.D., MacKenzie, A.R., Barkley, M.P., Carslaw, N., Carver, G.D., Chappell, N.A., Coe, H., Collier, C., Commane, R., Davies, F., Davison, B., DiCarlo, P., Di Marco, C.F., Dorsey, J.R., Edwards, P.M., Evans, M.J., Fowler, D., Furneaux, K.L., Gallagher, M., Guenther, A., Heard, D.E., Helfter, C., Hopkins, J., Ingham, T., Irwin, M., Jones, C., Karunaharan, A., Langford, B., Lewis, A.C., Lim, S.F., MacDonald, S.M., Mahajan, A.S., Malpass, S., McFiggans, G., Mills, G., Misztal, P., Moller, S., Monks, P.S., Nemitz, E., Nicolas-Perea, V., Oetjen, H., Oram, D.E., Palmer, P.I., Phillips, G.J., Pike, R., Plane, J.M.C., Pugh, T., Pyle, J.A., Reeves, C.E., Robinson, N.H., Stewart, D., Stone, D., Whalley, L.K., and Yang, X.: Overview: oxidant and particle photochemical processes above a south-east Asian tropical rainforest (the OP3 project): Introduction, rationale, location characteristics and tools, Atmos. Chem. Phys., 10, 169–199, doi: 10.5194/acp-10-169-2010, 2010.

Hewitt, C.N., MacKenzie, A.R., Di Carlo, P., Di Marco, C.F., Dorsey, J.R., Evans, M., Fowler, D., Gallagher, M.W., Hopkins, J.R., Jones, C.E., Langford, B., Lee, J.D., Lewis, A.C., Lim, S.F., McQuaid, J., Misztal, P., Moller, S.J., Monks, P.S., Nemitz, E., Oram, D.E., Owen, S.M., Phillips, G.J., Pugh, T.A.M., Pyle, J.A., Reeves, C.E., Ryder, J., Siong, J., Skiba, U., and Stewart, D.J.:

Nitrogen management is essential to prevent tropical oil palm plantations from causing ground-level ozone pollution, P. Natl. Acad. Sci. USA, 106, 18447–18451, doi: 10.1073/pnas.0907541106, 2009.

Hollaway, M.J., Arnold, S.R., Collins, W.J., Folberth, G., and Rap, A.: (2017), Sensitivity of midnineteenth century tropospheric ozone to atmospheric chemistry-vegetation interactions, J. Geophys. Res.-Atmos., 122, 2452–2473, doi:10.1002/2016JD025462, 2017.

Hooijer, A., Page, S., Canadell, J.G., Silvius, M., Kwadijk, J., Wösten, H., and Jauhiainen, J.: Current and future CO2 emissions from drained peatlands in Southeast Asia, Biogeosciences, 7, 1505–1514, doi: 10.5194/bg-7-1505-2010, 2010.

Houweling, S., Dentener, F., and Lelieveld, J.: The impact of nonmethane hydrocarbon compounds on tropospheric photochemistry, J. Geophys. Res., 103, 10,673–10,696, doi: 10.1029/97JD03582, 1998.

Hoyle, C.R., Berntsen, T., Myhre, G., and Isaksen, I.S.A.: Secondary organic aerosol in the global aerosol–chemical transport model Oslo CTM2, Atmos. Chem. Phys., 7, 5675–5694, doi: 10.5194/acp-7-5675-2007, 2007.

Indonesian Ministry of Agriculture: Tree Crop Estate Statistics of Indonesia 2015–2017, Directorate General of Estate Crops, Ministry of Agriculture, Indonesia, 2017.

Indrarto, G.B., Murharjanti, P., Khatarina, J., Pulungan, I., Ivalerina, F., Rahman, J., Prana, M.N., Resosudarmo, I.A.P., and Muharrom, E.: The context of REDD+ in Indonesia: Drivers, agents and institutions (Working Paper 92), CIFOR, Bogor, Indonesia, 2012.

Jacob, D.J.: Introduction to Atmospheric Chemistry, Princeton University Press, 1999.

Jardine, A.B., Jardine, K.J., Fuentes, J.D., Martin, S.T., Martins, G., Durgante, F., Carneiro, V., Higuchi, N., Manzi, A.O., and Chambers, J.Q.: Highly reactive light-dependent monoterpenes in the Amazon, Geophys. Res. Lett., 42, 1576–1583, doi: 10.1002/2014GL062573, 2015.

Jardine, K.J., Jardine, A.B., Holm, J.A., Lombardozzi, D.L., Negron-Juarez, R.I., Martin, S.T., Beller, H.R., Gimenez, B.O., Higuchi, N., and Chambers, J.Q.: Monoterpene 'thermometer' of tropical forest-atmosphere response to climate warming, Plant Cell Environ., 40, 441–452, doi: 10.1111/pce.12879, 2017.

Jokinen, T., Berndt, T., Makkonen, R., Kerminen, V.-M., Junninen, H., Paasonen, P., Stratmann, F., Herrmann, H., Guenther, A.B., Worsnop, D.R., Kulmala, M., Ehn, M., and Sipilä, M.: Production of extremely low volatile organic compounds from biogenic emissions: Measured yields and atmospheric implications, P. Natl. Acad. Sci. USA, 112, 7123–7128, doi: 10.1073/pnas.1423977112, 2015.

Kane, S.M., Caloz, F., and Leu, M.-T.: Heterogeneous uptake of gaseous N_2O_5 by $(NH_4)_2SO_4$, NH_4HSO_4, and H_2SO_4 aerosols, J. Phys. Chem. A, 105, 6465–6470, doi: 10.1021/jp010490x , 2001.

Kelly, J.M., Doherty, R.M., O'Connor, F., and Mann, G.W.: The impact of biogenic, anthropogenic, and biomass burning volatile organic compound emissions on regional and seasonal variations in secondary organic aerosol, Atmos. Chem. Phys., 18, 7393–7422, doi: 10.5194/acp-18-7393-2018, 2018.

Klinger, L.F., Li, Q.-J., Guenther, A.B., Greenberg, J.P., Baker, B., and Bai, J.-H.: Assessment of volatile organic compound emissions from ecosystems of China, J. Geophys. Res.-Atmos., 107, 4603, doi: 10.1029/2001JD001076, 2002.

Knote, C., Tuccella, P., Curci, G., Emmons, L., Orlando, J. J., Madronich, S., Baró, R., Jiménez-Guerrero, P., Luecken, D., Hogrefe, C., Forkel, R., Werhahn, J., Hirtl, M., Perez, J. L., San José, R., Giordano, L., Brunner, D., Yahya, K., and Zhang, Y.: Influence of the choice of gas-phase mechanism on predictions of key gaseous pollutants during the AQMEII phase-2 intercomparison, Atmos. Environ., 115, 553–568, doi: 10.1016/j.atmosenv.2014.11.066, 2015.

Koch, D., Schmidt, G.A., and Field, C.V.: Sulfur, sea salt, and radionuclide aerosols in GISS ModelE, J. Geophys. Res., 111, D06206, doi: 10.1029/2004JD005550, 2006.

Koplitz, S.N., Mickley, L.J., Marlier, M.E., Buonocore, J.J., Kim, P.S., Liu, T., Sulprizio, M.P., DeFries, R.S., Jacob, D.J., Schwartz, J., Pongsiri, M., and Myers, S.S.: Public health impacts of the severe haze in Equatorial Asia in September–October 2015: Demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure, Environ. Res. Lett., 11, 094023, doi: 10.1088/1748-9326/11/9/094023, 2016.

Kotchenruther, R.A., Jaffe, D.A., and Jaeglé, L.: Ozone photochemistry and the role of peroxyacetyl nitrate in the springtime northeastern Pacific troposphere: Results from the Photochemical Ozone Budget of the Eastern North Pacific Atmosphere (PHOBEA) campaign, J. Geophys. Res., 106, 28,731–28,742, doi: 10.1029/2000JD000060, 2001.

Kroll, J.H., Ng, N.L., Murphy, S.M., Flagan, R.C., and Seinfeld, J.H.: Secondary organic aerosol formation from isoprene photooxidation under high-NO_X conditions, Geophys. Res. Lett., 32, L18808, doi: 10.1029/2005GL023637, 2005.

Lacis, A.A., Wuebbles, D.J., and Logan, J.A.: Radiative forcing of climate by changes in the vertical distribution of ozone, J. Geophys. Res., 95, 9971–9981, doi: 10.1029/JD095iD07p09971, 1990.

Lamarque, J.-F., Bond, T.C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M.G., Shindell, D., Smith, S.J., Stehfest, E., Van Aardenne, J., Cooper, O.R., Kainuma, M., Mahowald, N., McConnell, J.R., Naik, V., Riahi, K., and van Vuuren,

D.P.: Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application, Atmos. Chem. Phys., 10, 7017–7039, doi: 10.5194/acp-10-7017-2010, 2010.

Langford, B., Misztal, P.K., Nemitz, E., Davison, B., Helfter, C., Pugh, T.A.M., MacKenzie, A.R., Lim, S.F., and Hewitt, C.N.: Fluxes and concentrations of volatile organic compounds from a South-East Asian tropical rainforest, Atmos. Chem. Phys., 10, 8391–8412, doi: 10.5194/acp-10-8391-2010, 2010.

Lathière, J., Hauglustaine, D.A., Friend, A.D., De Noblet-Ducoudré, N., Viovy, N., and Folberth, G.A.: Impact of climate variability and land use changes on global biogenic volatile organic compound emissions, Atmos. Chem. Phys., 6, 2129–2146, doi: 10.5194/acp-6-2129-2006, 2006.

Malaysian Palm Oil Board (MPOB), Economics and Industry Development Division, Statistics: bepi.mpob.gov.my, accessed: 25 August 2018.

Margono, B.A., Potapov, P.V., Turubanova, S., Stolle, F., and Hansen, M.C.: Primary forest cover loss in Indonesia over 2000–2012, Nat. Clim. Change, 4, 730–735, doi: 10.1038/nclimate2277, 2014.

McPeters, R., Kroon, M., Labow, G., Brinksma, E., Balis, D., Petropavlovskikh, I., Veefkind, J., Bhartia, P., and Levelt, P.: Validation of the aura ozone monitoring instrument total column ozone product, J. Geophys. Res.-Atmos., 113, D15S14, doi:10.1029/2007JD008802, 2008.

Miettinen, J., Hooijer, A., Vernimmen, R., Liew, S.C., and Page, S.E.: From carbon sink to carbon source: Extensive peat oxidation in insular Southeast Asia since 1990, Environ. Res. Lett., 12, 024014, doi: 10.1088/1748-9326/aa5b6f, 2017.

Misztal, P.K., Nemitz, E., Langford, B., Di Marco, C.F., Phillips, G.J., Hewitt, C.N., MacKenzie, A.R., Owen, S.M., Fowler, D., Heal, M.R., and Cape, J.N.: Direct ecosystem fluxes of volatile organic compounds from oil palms in South-East Asia, Atmos. Chem. Phys., 11, 8995–9017, doi: 10.5194/acp-11-8995-2011, 2011.

Moxim, W.J., Levy II, H., and Kasibhatla, P.S.: Simulated global tropospheric PAN: Its transport and impact on NOx, J. Geophys. Res., 101, 12,621–12,638, doi: 10.1029/96JD00338, 1996.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., and Zhang, H.: Anthropogenic and natural radiative forcing, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M., Cambridge University Press, Cambridge, United Kingdom and New York, 2013.

Page, S.E., Siegert, F., Rieley, J.O., Boehm, H.-D.V., Jaya, A., and Limin, S.: The amount of carbon released from peat and forest fires in Indonesia during 1997, Nature, 420, 61–65, doi: 10.1038/nature01131, 2002.

Rap, A., Scott, C.E., Reddington, C.L., Mercado, L., Ellis, R.J., Garraway, S., Evans, M.J., Beerling, D.J., MacKenzie, A.R., Hewitt, C.N., and Spracklen, D.V.: Enhanced global primary production by biogenic aerosol via diffuse radiation fertilization, Nat. Geosci., et al., Nat Geoscience, doi: 10.1038/s41561-018-0208-3, 2018.

Schmidt, G.A., Kelley, M., Nazarenko, L., Ruedy, R., Russell, G.L., Aleinov, I., Bauer, M., Bauer, S.E., Bhat, M.K., Bleck, R., Canuto, V., Chen, Y.-H., Cheng, Y., Clune, T.L., Del Genio, A., de Fainchtein, R., Faluvegi, G., Hansen, J.E., Healy, R.J., Kiang, N.Y., Koch, D., Lacis, A.A., LeGrande, A.N., Lerner, J., Lo, K.K., Matthews, E.E., Menon, S., Miller, R.L., Oinas, V., Oloso, A.O., Perlwitz, J.P., Puma, M.J., Putman, W.M., Rind, D., Romanou, A., Sato, M., Shindell, D.T., Sun, S., Syed, R.A., Tausnev, N., Tsigaridis, K., Unger, N., Voulgarakis, A., Yao, M.-S., and Zhang, J.: Configuration and assessment of the GISS ModelE2 contributions to the CMIP5 archive, J. Adv. Model. Earth Sy., 6, 141–184, doi: 10.1002/2013MS000265, 2014.

Schultz, M.G., Heil, A., Hoelzemann, J.J., Spessa, A., Thonicke, K., Goldammer, J.G., Held, A.C., Pereira, J.M.C., and van het Bolscher, M.: Global wildland fire emissions from 1960 to 2000, Global Biogeochem. Cy., 22, GB2002, doi: 10.1029/2007GB003031, 2008.

Scott, C.E., Arnold, S.R., Monks, S.A., Asmi, A., Paasonen, P., and Spracklen, D.V.: Substantial large-scale feedbacks between natural aerosols and climate, Nat Geoscience, 11, 44–48, doi: 10.1038/s41561-017-0020-5, 2018.

Scott, C.E., Monks, S.A., Spracklen, D.V., Arnold, S.R., Forster, P.M., Rap, A., Äijälä, M., Artaxo, P., Carslaw, K.S., Chipperfield, M.P., Ehn, M., Gilardoni, S., Heikkinen, L., Kulmala, M., Petäjä, T., Reddington, C.L.S., Rizzo, L.V., Swietlicki, E., Vignati, E., and Wilson, C.: Impact on short-lived climate forcers increases projected warming due to deforestation, Nat. Commun., 9:157, 1–9, doi: 10.1038/s41467-017-02412-4, 2018.

Scott, C.E., Monks, S.A., Spracklen, D.V., Arnold, S.R., Forster, P.M., Rap, A., Carslaw, K.S., Chipperfield, M.P., Reddington, C.L.S., and Wilson, C.: Impact on short-lived climate forcers (SLCFs) from a realistic land-use change scenario via changes in biogenic emissions, Faraday Discuss., 200, 101–120, doi: 10.1039/c7fd00028f, 2017.

Shindell, D.T., Faluvegi, G., and Bell, N.: Preindustrial-to-present-day radiative forcing by tropospheric ozone from improved simulations with the GISS chemistry-climate GCM, Atmos. Chem. Phys., 3, 1675–1702, doi: 10.5194/acp-3-1675-2003, 2003.

Shindell, D.T., Faluvegi, G., Unger, N., Aguilar, E., Schmidt, G.A., Koch, D.M., Bauer, S.E., and Miller, R.L.: Simulations of preindustrial, present-day, and 2100 conditions in the NASA GISS

composition and climate model G-PUCCINI, Atmos. Chem. Phys., 6, 4427–4459, doi: 10.5194/acp-6-4427-2006, 2006.

Shindell, D.T., Pechony, O., Voulgarakis, A., Faluvegi, G., Nazarenko, L., Lamarque, J.-F., Bowman, K., Milly, G., Kovari, B., Ruedy, R., and Schmidt, G.A.: Interactive ozone and methane chemistry in GISS-E2 historical and future climate simulations, Atmos. Chem. Phys., 13, 2653–2689, doi: 10.5194/acp-13-2653-2013, 2013.

Silva, S.J., Heald, C.L., Geddes, J.A., Austin, K.G., Kasibhatla, P.S., and Marlier, M.E.: Impacts of current and projected oil palm plantation expansion on air quality over Southeast Asia, Atmos. Chem. Phys., 16, 10621–10635, doi: 10.5194/acp-16-10621-2016, 2016.

Sodhi, N.S., Koh, L.P., Brook, B.W., and Ng, P.K.L.: Southeast Asian biodiversity: An impending disaster, Trends Ecol. Evol., 19, 654–660, doi: 10.1016/j.tree.2004.09.006, 2004.

Stavrakou, T., Müller, J.-F., Bauwens, M., De Smedt, I., Van Roozendael, M., Guenther, A., Wild, M., and Xia, X.: Isoprene emissions over Asia 1979-2012: Impact of climate and land-use changes, Atmos. Chem. Phys., 14, 4587–4605, doi: 10.5194/acp-14-4587-2014, 2014.

Stockwell, W.R., Kirchner, F., Kuhn, M., and Seefeld, S.: A new mechanism for regional atmospheric chemistry modeling, J. Geophys. Res., 102, 25,847–25,879, doi: 10.1029/97JD00849, 1997.

Surratt, J.D., Chan, A.W.H., Eddingsaas, N.C., Chan, M., Loza, C.L., Kwan, A.J., Hersey, S.P., Flagan, R.C., Wennberg, P.O., and Seinfeld, J.H.: Reactive intermediates revealed in secondary organic aerosol formation from isoprene, P. Natl. Acad. Sci. USA, 107, 6640–6645, doi: 10.1073/pnas.0911114107, 2010.

Thompson, A.M., Tao, W.-K., Pickering, K.E., Scala, J.R., and Simpson, J.: Tropical deep convection and ozone formation, B. Am. Meteorol. Soc., 78, 1043–1054, doi: 10.1175/1520-0477(1997)078<1043:TDCAOF>2.0.CO;2, 1997.

Tilmes, S., Lamarque, J.-F., Emmons, L.K., Conley, A., Schultz, M.G., Saunois, M., Thouret, V., Thompson, A.M., Oltmans, S.J., Johnson, B., and Tarasick, D.: Technical Note: Ozonesonde climatology between 1995 and 2011: Description, evaluation and applications, Atmos. Chem. Phys., 12, 7475–7497, doi: 10.5194/acp-12-7475-2012, 2012.

Tsigaridis, K., Daskalakis, N., Kanakidou, M., Adams, P.J., Artaxo, P., Bahadur, R., Balkanski, Y., Bauer, S.E., Bellouin, N., Benedetti, A., Bergman, T., Berntsen, T.K., Beukes, J.P., Bian, H., Carslaw, K.S., Chin, M., Curci, G., Diehl, T., Easter, R.C., Ghan, S.J., Gong, S.L., Hodzic, A., Hoyle, C.R., Iversen, T., Jathar, S., Jimenez, J.L., Kaiser, J.W., Kirkevåg, A., Koch, D., Kokkola, H., Lee, Y.H., Lin, G., Liu, X., Luo, G., Ma, X., Mann, G.W., Mihalopoulos, N., Morcrette, J.-J., Müller, J.-F., Myhre, G., Myriokefalitakis, S., Ng, N.L., O'Donnell, D., Penner, J.E., Pozzoli, L., Pringle, K.J., Russell, L.M., Schulz, M., Sciare, J., Seland, Ø., Shindell, D.T., Sillman, S., Skeie, R. B., Spracklen,

D., Stavrakou, T., Steenrod, S.D., Takemura, T., Tiitta, P.,Tilmes, S., Tost, H., van Noije, T., van Zyl, P.G., von Salzen, K., Yu, F., Wang, Z., Wang, Z., Zaveri, R. A., Zhang, H., Zhang, K., Zhang, Q., and Zhang, X.: The AeroCom evaluation and intercomparison of organic aerosol in global models, Atmos. Chem. Phys, 14, 10845–10895, doi: 10.5194/acp-14-10845-2014, 2014.

Tsigaridis, K. and Kanakidou, M.: Secondary organic aerosol importance in the future atmosphere, Atmos. Environ., 41, 4682–4692, doi: 10.1016/j.atmosenv.2007.03.045, 2007.

Turnock, S.T., Wild, O., Dentener, F.J., Davila, Y., Emmons, L.K., Flemming, J., Folberth, G.A., Henze, D.K., Jonson, J.E., Keating, T.J., Kengo, S., Lin, M., Lund, M., Tilmes, S., and O'Connor, F.M.: The impact of future emission policies on tropospheric ozone using a parameterized approach, Atmos. Chem. Phys., 18, 8953–8978, doi: 10.5194/acp-18-8953-2018, 2018.

Unger, N.: Human land-use-driven reduction of forest volatiles cools global climate, Nat. Clim. Change, 4, 907–910, doi: 10.1038/NCLIMATE2347, 2014a.

Unger, N.: On the role of plant volatiles in anthropogenic global climate change, Geophys. Res. Lett., 41, 8563–8569, doi: 10.1002/2014GL061616, 2014b.

Unger, N., Bond, T.C., Wang, J.S., Koch, D.M., Menon, S., Shindell, D.T., and Bauer, S.: Attribution of climate forcing to economic sectors, P. Natl. Acad. Sci. USA, 107, 3382–3387, doi: 10.1073/pnas.0906548107, 2010.

van der Werf, G.R., Morton, D.C., DeFries, R.S., Olivier, J.G., Kasibhatla, P.S., Jackson, R.B., Collatz, G.J., and Randerson, J.T.: CO2 emissions from forest loss, Nat. Geosci., 2, 737–738, doi: 10.1038/ngeo671, 2009.

van der Werf, G.R., Randerson, J.T., Giglio, L., Collatz, G.J., Kasibhatla, P.S., and Arellano Jr., A.F.: Interannual variability in global biomass burning emissions from 1997 to 2004, Atmos. Chem. Phys., 6, 3423–3441, doi: 10.5194/acp-6-3423-2006, 2006.

Vermeulen, S. and Goad, N.: Towards better practice in smallholder palm oil production, Natural Resource Issues Series (No. 5), International Institute for Environment and Development, London, UK, 2006.

Warwick, N.J., Archibald, A.T., Ashworth, K., Dorsey, J., Edwards, P.M., Heard, D.E., Langford, B., Lee, J., Misztal, P.K., Whalley, L.K., and Pyle, J.A.: A global model study of the impact of land-use change in Borneo on atmospheric composition, Atmos. Chem. Phys., 13, 9183–9194, doi: 10.5194/acp-13-9183-2013, 2013.

Wild, O., Fiore, A.M., Shindell, D.T., Doherty, R.M., Collins, W.J., Dentener, F.J., Schultz, M.G., Gong, S., MacKenzie, I.A., Zeng, G., Hess, P., Duncan, B.N., Bergmann, D.J., Szopa, S., Jonson, J.E., Keating, T.J., and Zuber, A.: Modelling future changes in surface ozone: A parameterized approach, Atmos. Chem. Phys., 12, 2037–2054, doi: 10.5194/acp-12-2037-2012, 2012.

Wolfe, G.M., Kaiser, J., Hanisco, T.F., Keutsch, F.N., de Gouw, J.A., Gilman, J.B., Graus, M., Hatch, C.D., Holloway, J., Horowitz, L.W., Lee, B.H., Lerner, B.M., Lopez-Hilifiker, F., Mao, J., Marvin, M.R., Peischl, J., Pollack, I.B., Roberts, J.M., Ryerson, T.B., Thornton, J.A., Veres, P.R., and Warneke, C.: Formaldehyde production from isoprene oxidation across NOx regimes, Atmos. Chem. Phys., 16, 2597–2610, doi: 10.5194/acp-16-2597-2016, 2016.

Wong, A.Y.H., Tai, A.P.K., and Ip, Y.-Y.: Attribution and statistical parameterization of the sensitivity of surface ozone to changes in leaf area index based on a chemical transport model, J. Geophys. Res.-Atmos., 123, 1883–1898, doi: 10.1002/2017JD027311, 2018.

WRI: CAIT Climate Data Explorer [Electronic database], World Resources Institute, http://cait.wri.org, 2015.

Yu, F.: A secondary organic aerosol formation model considering successive oxidation aging and kinetic condensation of organic compounds: Global scale implications, Atmos. Chem. Phys., 11, 1083–1099, doi: 10.5194/acp-11-1083-2011, 2011.

Zhang, H., Yee, L.D., Lee, B.H., Curtis, M.P., Worton, D.R., Isaacman-VanWertz, G., Offenberg, J.H., Lewandowski, M., Kleindienst, T.E., Beaver, M.R., Holder, A.L., Lonneman, W.A., Docherty, K.S., Jaoui, M., Pye, H.O.T., Hu, W., Day, D.A., Campuzano-Jost, P., Jimenez, J.L., Guo, H., Weber, R.J., de Gouw, J., Koss, A.R., Edgerton, E.S., Brune, W., Mohr, C., Lopez-Hilfiker, F.D., Lutz, A., Kreisberg, N.M., Spielman, S.R., Hering, S.V., Wilson, K.R., Thornton, J.A., and Goldstein, A.H.: Monoterpenes are the largest source of summertime organic aerosol in the southeastern United States, P. Natl. Acad. Sci. USA, 115, 2038–2043, doi: 10.1073/pnas.1717513115, 2018.