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Interactive Comment

Interactive comment on "Isoprene emissions over Asia 1979–2012: impact of climate and land use changes" *by* T. Stavrakou et al.

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We would like to thank the reviewer for his/her positive evaluation of the manuscript and for the useful comments and suggestions. Below we address the raised concerns. The reviewer's comments are *italicized*.

Stavrakou et al. improve upon earlier studies of biogenic isoprene emissions from Asia, a region undergoing dramatic land-use and climate changes in recent decades, by applying the MEGAN emissions model coupled to a canopy vegetation model. Applying base conditions (meteorology, static vegetation map, and emission factors), they calculate the spatial and temporal changes in isoprene emissions over the period 1979-2012. Starting from their base simulation, the authors perform four additional simu-

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lations to correct for previously identified biases using observation-derived emission factors, and the observed trends in land-use and solar radiation. They find that their best bottom-up isoprene emission trends and distributions are consistent with those derived using GOME-2 formaldehyde (HCHO) columns.

The information provided in this paper is valuable to both the emissions and air quality communities as it clearly highlights that biogenic isoprene emissions in Asia are changing significantly in response to environmental changes and this will have important consequences for regional air quality. The study highlights the improvement in modeled estimates of biogenic emission in Asia when constraints from limited ground-based observations are included -enhanced observational network in that region will lead to better-informed emission models. Overall the paper is well-written with valuable information for emission and air pollution modeling. There is some choppy organization (see general comments below) which can be easily addressed. The paper is appropriate for publication in ACP after minor corrections have been made.

General Comment:

1. *Before discussing the trends in Asian isoprene emissions, the authors should evaluate the isoprene fluxes from their base simulation against observations in Asia, preferably ground-based. This will convince the readers that the current model setup suffers from similar biases as noted by Langford et al. (2010) and that the corrections applied in subsequent simulations indeed improve upon the base simulation. Thus, it would be helpful to evaluate the base isoprene fluxes for a particular time period (e.g. 2005 following the discussion in section 4/figure 7) against measurements from OP3 and measurements from other regions wherever available. For example, observational estimates of isoprene fluxes from other parts of Asia are available (Bai et al., 2004; Geron et al., 2006; Varshney and Singh, 2003; Singh et al., 2007; Singh et al., 2008).*

We followed this very good suggestion and included comparisons of our inventory results against two campaigns in Asia (Section 6): the OP3 campaign (Langford et al., 2010) and measurements at a tropical plantation in Yunnan, China (Baker et al., 2005). Note that most studies mentioned by the reviewer (Geron et al., 2006; Varshney and Singh, 2003; Singh et al., 2007; Singh et al., 2008) report enclosure measurements of emission factors on a dry weight basis (typically in μg g^{-1} h^{-1}) for specific plant species, and not above canopy emission rates with which we could evaluate our inventory. The study of Bai et al. (2004) reports the same emission rate measurements as the study of Baker et al. (2005).

We added the following text discussing the comparisons with ground-based measurements:

"We evaluate the inventory against the tower measurements of the OP3 (Oxidant and Particle Photochemical Processes above a South-East Asian Rainforest) project (Hewitt et al., 2010) at the Bukit Atur station in the Danum Valley region of Sabah, Malaysia (4.98°N, 117.84°E). The measurements were carried out over two four week periods with phase 1 (OP3-I) taking place during the months of April and May 2008 and phase 2 (OP3-III) between June and July 2008. The comparison of calculated fluxes with the measurements (Fig. 11) confirms the strong overestimation of the basal emission rate for tropical forests in Southeast Asia (Langford et al., 2010). The average simulated fluxes in S0 are overestimated by factors of about 7 and 5 during the wet (phase 1) and the dry season (phase 2), respectively. These larger factors compared to the factor of 4.1 inferred by Langford et al. (2010) are due to the larger average BER (10 mg m^{-2} h^{-1}) at the location of Bukit Atur in our simulation S0 compared to the basal emission rate of 6.6 mg m^{-2} h^{-1} used by Langford et al. (2010). Adopting the latter BER value in our simulations would lead to overestimation factors of 4.5 and 3.3 during the two phases, in excellent agreement with Langford et al. (2010). The factor of $\sim$2 higher emissions during the dry season compared to the wet season

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are only partly explained by the dependece of emissions on temperature and radiation in the MEGAN model, since the average temperature and radiation levels were only moderately higher during phase 2 compared to phase 1 (by 0.5 K and 25%, respectively). Changes in phenology are therefore the most likely cause for the higher apparent basal emission rate during the dry season compared with the wet season, by a factor of about 1.4 according to the model simulations.

In contrast with the seasonal variation discussed above, the emissions of isoprene (also monoterpenes) measured by eddy covariance above a tropical plantation of rubber trees (*Hevea brasiliensis*) in the Xishuangbanna Gardens (21.92°N, 101.27°E), Yunnan, South China, exhibited much higher values in the wet season than in the dry season (Baker et al., 2005). The average daytime isoprene emissions were found to be 1 and 0.15 mgC m^{-2} s^{-1} during the wet season (July 2002) and the dry season (February-March 2003), respectively, whereas our MEGAN-based inventory (S0) predicts higher emissions during the dry season (0.64 mgC m^{-2} s^{-1}) than in the wet season (0.44 mgC m^{-2} s^{-1}), due to generally lower cloudiness and higher temperatures and radiation levels during the dry season. As discussed by Baker et al. (2005), the lower dry season fluxes of monoterpenes result from the drought deciduous nature of the main monoterpene emitter, *Hevea brasiliensis*, which is however a low isoprene emitter. The very low dry season isoprene fluxes were very probably caused by extreme water stress conditions (Baker et al., 2005). The soil moisture activity factor is however equal to unity at all times in 2002/2003, based on the MEGAN parameterization (Guenther et al., 2006) using the ECMWF wilting point and soil moisture fields. In fact, the severe drought at the site in February/March 2003 is not recorded in the ERA-Interim data which does not even show lower soil moisture content values in this period compared to other months of the year. The soil moisture activity factor is very uncertain, as it has been found to be very dependent on the choice of the soil moisture and wilting point database (Müller et al., 2008, Marais et al., 2012, Tawfik et al., 2012, Sindelarova et al., 2014): for example, the reduction in

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global annual emissions due to this activity factor ranges between 7% (Guenther et al., 2006) and 50% (Sindelarova et al., 2014)."

2. *In terms of the organization, section 4 should be moved before section 3. Section 6.1 belongs as a sub-section in Section 2.*

   Section 4 includes discussion of the isoprene emissions per country across the simulations S0-S4, and, to our opinion, should not be placed before Section 3 where the results of the S0-S4 simulations are first presented. Section 7.1 of the revised version describes the inversion set-up in a global model. By moving this in Section 2 there is a risk of confusion between bottom-up (Section 2) and the top-down (Section 7.1) simulation setups. We therefore preferred to keep the current organization of the sections.

Specific Comments:

1. *Abstract, line 8-13: The authors should mention that they incorporated these factors (changes in land-use, solar radiation etc.) to correct for the biases identified in previous studies and also to account for deficiencies in meteorological inputs that have important implications for simulating trends and variability in isoprene emissions in this region.*

   We inserted the following text: “In order to remedy for known biases identified in previous studies, and to improve the simulation of interannual varability and trends in emissions, this study incorporates..."

2. *Line 18-19: The authors attribute the variability and trends in emissions to changes in temperature and solar radiation here while including soil moisture as one of the main drivers in the conclusions (page 29572, line 1). I would suggest being consistent in the abstract and the main text. Also see comment 14 below.*

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This is entirely correct. The text now reads “Changes in temperature, solar radiation are the major drivers of the interannual variability and trend in the emissions, except over semi-arid areas such as Northwestern China, Pakistan and Kazakhstan, where soil moisture is by far the main cause for interannual emission changes. "

3. *Line 19-22: Remind the readers that the trend discussed here is from the base simulation that does not include the additional factors considered in sensitivity simulations.*

   We changed the sentence to “In our base simulation, an annual positive flux trend of 0.2% and 0.52% through the entire period is found in Asia and China, respectively, related to positive trend in temperature and solar radiation."

4. *Page 29554, Line 10: A reference is needed for “...since crops are known to be weaker isoprene emitters than the forests they substitute."*

   A reference is added here (Guenther et al. 2006).

5. *Page 29554, Line 15: For better clarity, the sentence should be revised to: “Crops in China are being converted to tree plantations (e.g....) for economic reasons, resulting in..."*

   Changed as suggested.

6. *Page 29555, Line 16: The sentence “Their estimation is uncertain, as it relies..." needs to be rephrased for clarity.*

   Changed to “Their estimation is uncertain due to possible errors in the emission capacities for both natural forests and managed landscapes."

7. *Page 29556, Line 19: Remove “literature"*

Removed.

8. *Page 29558, Line 13: The word “realized" reads awkward here. Replace with perhaps “accomplished"*

   Replaced by “achieved".

9. *Page 29559, Lines 9-10: What level of uncertainty is introduced in the calculated emission trends with the use of climatological mean MODIS LAIs prior to 2002, particularly, since emission flux rate is a function of LAI (equation 2)? Are the same LAIs used for all simulations S0 through S4?*

   The same LAIs are used for all simulations. Additional calculations were performed to determine the role of LAI variability on the emissions. The following text has been added in Section 3:

   ”In order to assess the possible role of LAI interannual variability on isoprene emissions, we compare the trends in our base (S0) emissions between 2002 and 2012 (i.e. using LAI varying from year to year) with emission trends calculated using climatological LAI during the same period. The emission trends are almost unaffected over the whole domain (e.g. -0.221 and 0.237%/year using variable or climatological LAI, respectively) or in Southeast Asia (e.g. 0.148 and 0.160%/year over Indonesia). Larger changes are found over more arid areas such as Western India and Northwestern China (e.g. 0.796 and 0.439%/year over India). Noting that these regions are characterized by low LAI values (typically $<$1.5) for which the MODIS-based estimations are expected to be very uncertain, we conclude that the impact of LAI interannual variability is generally either small or uncertain."

10. *Page 29560, 2nd paragraph: It would be helpful to provide the basal emission factors for oil palm trees.*

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Here we use the parameterization of Mizstal et al.(2011) based on the average canopy temperature (T_c) and a basal emission rate of 22.8 mg m^{-2}h^{-1}, as now clearly stated in the text.

11. *Page 29561-29562: Discussion of Figure 4 should be presented before the discussion of Figure 5. Further, in relation to Figure 5, it would be helpful to provide a quantitative estimate of the dominant drivers of fluxes either in the Asian domain or in China by performing statistical correlation of fluxes with temperature, radiation, and soil moisture (since emissions are dependent on these time-varying factors). Similarly, a pattern correlation of the trends in Figure 4 is needed to quantitatively substantiate statements like "the increasing trend in emission is due to increases in the soil moisture activity factor, most likely reflecting positive trends in soil moisture..."*

    We included a new figure (Fig. 4) displaying the spatial distribution correlation coefficient between the emissions and the main meteorological drivers of the emissions. Furthermore, Fig. 5 (previously Fig. 4) now includes also the trend in the soil moisture activity factor. Those figures are presented as follows:

    "Figure 4 displays the distribution of the correlation coefficient between annual isoprene emissions in the S0 simulation and the main meteorological drivers of the emission, namely air temperature, above-canopy radiation and the soil moisture stress activity factor. Unsurprisingly, the calculated emissions are strongly correlated with PAR levels over most non-arid regions, and especially over forested areas. This is a consequence of both the direct effect of PAR on emissions (Eq. 2) and the indirect effect through the temperature activity factor (Eq. 4) and the dependence of leaf temperature on solar radiation (Müller et al., 2008). Compared to PAR, air temperature is less well correlated with the emissions in many regions, in part because it is leaf temperature, not air temperature, which drives the temperature activity factor. Furthermore, at extratropical

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latitudes, the emissions are likely better correlated with summertime temperature than with annual temperature, since most of the annual emissions take place during the summer. Over arid and semi-arid regions, soil moisture is clearly the main meteorological driver of interannual variability. Negative correlation coefficients between the emissions and the soil moisture activity factor over e.g. Eastern China result from the correlation of soil moisture with cloudiness which is itself anticorrelated with PAR. The same effect also explains the negative correlations between emission and PAR over arid areas.

The spatial distribution of the 1979-2012 trends in isoprene emissions (as estimated by the standard S0 simulation) is generally well explained by the distribution of trends in temperature, radiation and the soil moisture activity factor (Fig. 5). Over non-arid areas, temperature and radiation dominate the behaviour of the resulting flux. Over arid and semi-arid regions (Kazakhstan, Pakistan, Western India and Northwestern China), however, positive trends in emissions are primarily caused by increasing trends in soil moisture in those areas. "

12. *Page 29563, Lines 8-21: As the other reviewers note, the discussion of the relationship between emissions and ONI is abrupt and needs a preface in Section 1. Also, it is not clear how the isoprene flux anomaly is calculated? Is this anomaly with respect to the mean of 1979-2012?*

    We included the following sentence in the abstract: “The isoprene flux anomaly over the whole domain and studied period is found to be strongly correlated with the Oceanic Niño Index ($r = 0.73$), with positive (negative) anomalies related to El Niño (La Niña) years." The reviewer’s guess is correct: the isoprene flux anomaly is calculated with respect to the 1979-2012 mean. This is now added in Section 3.

13. *Page 29564, Line 25: Although the authors discuss S3 results for 2005, Figure 7*

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does not show fluxes for S3. This oversight should be corrected.

The S4 simulation combines the effects of solar radiation updates in India, China and Japan, and oil palm plantations in Indonesia and Malaysia (as explained in the caption). These updates are independent, since they apply to different countries. The results of the S4 simulation are therefore identical to those of S3 over Indonesia and Malaysia. A clarification is now added in the figure caption (now Figure 8).

14. *Page 29566, Section 5: To me, this section is an extension of the discussion of variability and trends in isoprene emission in the S0 simulation (section 2). Perhaps the authors could combine the two to make the text and figures more concise. As an example, the black line in Figure 9 for China is the same as in Figure 5 (second panel from the top), although it appears that the calculated trends are different (why is it 0.42%/yr in Fig 9 versus 0.52%/yr in Fig 5). Additionally, all panels in Figure 9 do not show fluxes for the 5 simulations (S0-S4). Is there a reason for showing selective simulations for each country? If so, it should be stated clearly, although I would recommend showing all simulations to be consistent as otherwise this would be akin to cherry-picking to support conclusions.*

The emission trends over China in Figure 9 (0.42%/yr) and Figure 5 (0.52%/yr) in the S0 simulation are different because they apply to different periods: 1979-2005 in the first case, 1979-2012 in the second as shown in the horizontal axis of the plots. The reason for the shorter period in Figure 9 is explained by the lack of solar radiation data beyond 2005. This is mentioned in the first paragraph of Section 5.

The reviewer is right about the fact that panels of Figure 9 do not include all S0-S4 runs. The reason is that the updates in S0-S4 do not concern all countries. For example, in China, the results of S3 and S4 simulations are identical because oil palm plantations are implemented only in Indonesia and Malaysia. Similarly,

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S4 simulation over Malaysia and Indonesia is identical as S3 since solar radiation correction concerns only Japan, China, and India. A clarification is now included in the figure caption.

15. *Page 29571, line 24: replace "builts" with "builds"*

    Corrected.

16. *Page 29572, line 1: I suggest that the authors perform a quantitative analysis of the role of soil moisture in driving variability and trend in Asian isoprene emissions to support their conclusion statement "Temperature, solar radiation, and soil moisture are the main drivers of interannual variability.*

    As discussed above, soil moisture is now clearly shown to be the main driver of emission variability over (semi-)arid regions, as seen in the new Figures 4 and 5(d).

17. *Page 29572, line 15: The statement "...in better agreement with ground-based observations." needs to be supported by comparing the fluxes simulated in S4 (and S0) with ground-based observations.*

    See above (General comment 1). We have followed this suggestion and included comparisons with two measurement campaigns.

18. *Figures 1, 2, 4, 7, 8, and 10: The labels on the label bar are too small to read. Please use bigger and darker font.*

    Done.

19. *Figures: Please consider labeling panels as (a), (b), (c) and so on for figures that have greater than one panel.*

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Panels have been added in Figures 1, 2, and 4.

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