We thank the reviewers for the very useful and insightful comments which improved the manuscript. The responses to each comment are shown in the italic text below, followed by the revised manuscript.

Anonymous Referee #1

1) The importance of accurately estimating isoprene emissions for simulating photochemistry and aerosol formation in chemical transport models is well recognized. Yet, after two decades, the uncertainty of isoprene emission estimates still hovers around a factor of two. If the results from this study are upheld, the bias will have been significantly improved, although there is still considerable variability between model and observations for specific events. This paper builds off efforts to reduce this uncertainty by analyzing "measured" airborne isoprene fluxes over a range of ecosystems (from low emitters to higher emitters) over a large portion of California. The usefulness of this paper hinges strongly on the airborne flux technique introduced by Misztal et al. (2014). Overall, the results of the paper should be of interest to the ACP reader community, and with modifications, the paper is recommended for publication in ACP.

We thank very much the reviewer for these very encouraging and favorable comments.

2) It was unclear why three models (BEIGIS, MEGANv2.04, and MEGANv2.1) were evaluated with integrated ecoregion fluxes, while one model (CARB) was evaluated with footprint data. Because of the uncertainty in the size and shape of the footprints, it is recommended that the evaluation focus on all four models versus the integrated flux data across each ecosystem.

We appreciate this suggestion but we chose to compare ecoregion averaged data instead consistently for all the models. This choice is motivated by the need for quantitative evaluation of the ecologically distinct regions in California which each may represent different modeling challenges. The advantage of our approach is uncertainty reduction from short term-variability as well as fine footprint uncertainties, which average out to a large extent when integrated spatially and temporally.

In addition to comparing by ecoregion average, we showed the performance and discussed the challenges of using discrete fluxes and footprints to inspire future research which could make progress in understanding smaller spatial scale variabilities. While for many tracks the agreement is very good even at this extremely fine resolution, the lack of agreement in some cases does not necessarily mean that the model does not work well, but rather that it is more difficult to account for the random errors at fine scale (e.g. 2 km) than with appropriate averaging (e.g. >40 km). In a future study it would be beneficial for the aircraft to fly numerous times over the same tracks to achieve higher confidence in resolving fine contributions to fluxes, but we did not have the luxury of doing such repeated flights during the CABERNET campaign, and chose instead to obtain larger spatial coverage.

3) Because of the importance of trying to establish reliable airborne derived footprints for a variety of other trace gases (such as CO2, CH4, and N2O), maintaining the exploratory footprint section would be of interest to the community.

In response to this comment, we expand the footprint application section (2.4.2) to include clarification of "full-dome", and "half-dome" footprints derived from wavelet analysis. While this has been the first application of these footprints, the development still continues. Another manuscript in preparation (Yu et al., in prep.) is focused on further refinement and application of wavelet footprint approaches and *recently Vaughan et al., 2016 compared emission inventory emission factors using aircraft wavelet NOx flux over London using a parameterized aircraft footprint model.*

Specific comments:

4) Abstract: I am not a fan of abstracts written with paragraphs and references, but that is my personal preference. Suggest consulting ACP style guide to see if abstract follows protocol.

We keep gentle paragraphing in the abstract (the spaces between paragraphs have been removed). The citation to Guenther algorithm is necessary to indicate the version. The citation to Misztal et al. (2014) makes it clear that the paper is not repeating the information which has been presented earlier.

5) p.3, line 25: Since the CARB model was "improved" using the CABERNET measurements, evaluating it versus the other models using CABERNET measurements doesn't seem fair. Was any of the data set held out for an independent evaluation?

Both modeling and measurement efforts were occurring independently during and after CABERNET. The CARB model dataset has not been nudged yet in any way to measurement data so "was any data held out" does not apply. This way, the comparison is fair using the current CARB model which combines the latest developments in MEGAN but keeps improvements to regional BEIGIS infrastructure. Based on the comparison, there is still a scope to improve that model in different regions but the paper focuses on making fair comparison which will enable future improvements to the landcovers that the state might want to make. We make it now clear in the text that we did not use CABERNET fluxes to set the CARB emission factors.

6) p.4, lines 6-11: Use of the WRF model to provide temperature and PAR is mentioned. And it is mentioned that the temperature data are compared against observations. How reliable is the PAR data? Because of aerosol effects, we have found that PAR from WRF can easily be overestimated by 10%.

This is a great point. We have only evaluated the temperature which can be more uncertain close to the foothills where gradients are larger. We also expect uncertainty in the PAR data but they are expected to be less prone to spatial differences relative to temperature and also will be small because we chose the flight days to be completely cloudless. However, we point out that averaging and aerosol loading can also have influence on PAR.

7) p. 4, line 14: Sentence that begins with "BEIGIS" is fragmented and should be edited.

The sentence has been revised and now reads: "The Biogenic Emission Inventory processing model (BEIGIS) (Scott and Benjamin, 2003) was developed by CARB as a regional model specific to California, and is spatially resolved at 1 km^2 and temporally at 1 hour. BEIGIS uses California landcover, leaf mass, and emission rate databases with a geographic information system (GIS)."

8) p. 5: Fundamentally, isoprene emissions from all four models depend on the normalized isoprene emission fluxes assumed for quercus. Either in this section or in the supplemental materials, please summarize the normalized isoprene fluxes assumed for each model, whether they are assumed at the leaf, branch, or canopy level, whether fluxes vary by quercus species, and any references to support the flux values. Similarly, isoprene fluxes depend on quercus leaf biomass densities. How do these vary among the four models? Perhaps, one way of comparing the three/four models would be a table summarizing the attributes of the models that account for the

differences in estimated isoprene fluxes. The narrative as currently written only provides a superficial insight into model differences.

We report ecosystem scale fluxes which are not normalized to mass but instead to land area, then corrected to environmental conditions to obtain basal emission factors on a per land area basis. The landcover basal emission factors used in the models include species independent emission factors which have been derived from leaf and branch level measurement scaled by leaf area. What we are comparing is the measured ecosystem scale flux derived Basal Emission Factors and the model landcover Basal Emission Factors. This ecosystem scale comparison is unprecedented and consistently showed that these emissions were the highest from the oak woodlands which grow in specific altitude bands, but there were also substantial emissions in the mixed woodlands some of which could have been from other species such as Eucalyptus. As the reviewer suggests, we summarize the key attributes of the models, similarities and differences in the new table (Table 1).

9) p. 5, line 19 and other locations: In most situations, "which" should be preceded by a comma.

Done.

10) p. 5, section 2.1.4: Building on the "p. 5" comment above, more detail is needed to adequately describe the CARB hybrid model. Also, the sentence that begins "This regional model most closely agreed with the measured fluxes . . ." is confusing. My first reaction was why was a conclusion offered before the analysis and results sections. Then, I realized that the model had already been calibrated using the study data. This calibration needs to be clearly described here. All in all, this section is awkwardly written and needs to be reworked.

We apologize if the text gave the impression that the model had been calibrated. The model has not been calibrated on airborne data and was compared as it is. Initially we were considering to adapt the original MEGAN 2.1 which is currently the state-of-the-art version of the model but after a few pilot simulations it turned out that it would be difficult to keep previous regional enhancements in BEIGIS and it would be a major investment in modeling infrastructure change. After several preliminary pilot runs of the BEIGIS model with more enhancements from MEGAN 2.1, it was suggested that the hybrid model should perform similarly or even better than MEGAN 2.1 in CA regions. The sentence was to provide the explanation why the hybrid model was chosen and it has now been clarified to: "In preliminary runs (not shown), this regional model most closely agreed with the measured fluxes and is also currently used by CARB to estimate the BVOC emissions inventory for California. However, the model has not been calibrated on the measurement data to ensure that the comparison is fair."

As we mentioned in an earlier comment we summarize the detail for each model in the text and in Table 1. We have now improved the Sect. 2.1.4 in its clarity.

11) p. 8, section 2.4.1: The results of the paper rest on how the raw airborne data are converted into basal emission factors. The introductory paragraph mentions that more methodological details are provided in the supplement; however, these details are missing! These details are essential, but I didn't see them in the supplement.

We thank the reviewer for spotting this oversight in referencing the information which must have happened when we tried to move the specific text from the supplement to the manuscript. The methodological details on how airborne data are converted to basal emission factors were transferred from the supplementary information to the main manuscript and were available in Sect. 2.4.1 "Application of inverse G06 algorithm to the airborne fluxes". The text now correctly refers to Sect. 2.4.1 *which has been further expanded to include the estimation of BEF uncertainty. In addition, the full equation of the algorithm with its parameters (default) is now shown in SI.*

12) Lines 17-24, by themselves are insufficient, for convincing me of the accuracy of the airborne measurements in estimating basal fluxes. If possible, an estimate of errors associated with each of the six steps would be very helpful.

We add the estimates of errors in each step and discuss how they propagate to uncertainty in basal emission factors.

13) p. 9, lines 6-7: Clean up the font and subscripts for “dx0.5“, “h“, and “zm“.

Done.

14) p. 13, line 7-8: Provide references and/or analysis to support the role of landcover in heterogeneity and inaccuracy in overestimates/underestimates. Perhaps uncertainties in the aircraft data and their translation could be a contributor?

In this particular sentence we did not mean to downplay any kind of uncertainties. They are all important to be aware of. The sentence was meant to say that spatial heterogeneity (not just in species composition, but also vegetation cover fraction) can be responsible for potential inaccuracy that is much larger than other uncertainties. The aircraft data have some uncertainty but inherently represents the heterogeneities which are much more difficult to represent accurately in any model. We included “likely” because it is difficult to determine precisely the magnitude of each element.

15) p. 13, Section 3.3.2: In some of the tables and plots, emission amounts are used. Recommend sticking to fluxes. These could be area weighted to provide a perspective on the relative importance of different ecoregions.

We assume that the reviewer suggests to stick with flux terminology, but as we do not expect deposition from isoprene, using the emission terminology makes sense and we do this consistently in the graphs and tables.

16) p. 13, line 10: Add “,” after “model”.

Done.

17) p. 13, line 11: Remove “Supplement”.

Done.

18) p. 13, line 20: After “woodlands”, recommend showing specific ecoregion ids in parentheses.

Done.

19) p. 13, lines 22 and 25: Either ecoregion “7o” or “7a” is incorrect.

7a was a typo. It has been changed to 7o.

20) p. 13, line 23: Add comma after “emissions”.

Done.

21) p. 13, lines 22-28: Given that high isoprene fluxes were measured over areas that seemingly have low isoprene emitting vegetation, have the authors considered the possibility of anthropogenic sources – such as petrochemical related facilities, like tire manufacturing?

It is true that these areas in the Central Valley (7m, 7o) have little isoprene emitting vegetation in the model. However, the observed isoprene emissions were from vegetative regions, not from regions expected to have anthropogenic sources. We excluded significant anthropogenic isoprene contributions based on track analysis combined with Google Earth imagery. The aircraft observed gradual flux transitions characteristic of entering vegetative regions and the location of the vegetation was confirmed by Google Earth imagery.

22) p. 13, line 28: Add comma after "Overall".

Done.

23) p. 15, lines 2-7: While not necessarily a recommendation, this paragraph reads like it was extracted from a project report submitted to the state of California. Its style isn't consistent with most scientific journal articles.

We have revised these lines.

24) p. 15, line 21: Be more specific on "other recently available tools".

We added: "...such as highly sensitive time-of-flight mass spectrometry".

25) Figure 1: Consider removing the portions of the flight tracks where flux data were unavailable.

We appreciate the suggestion but we want to inform the reader where the track was, because even if the flux was not available the concentrations from those portions of tracks may still be valid.

26) Figure 2: "GAP's" should be defined. Plots c and d should be reversed to match caption.

GAP has been defined earlier in the text. We thank the reviewer for spotting the mismatch in the caption, which has now been corrected.

27) Figure 3: The text should discuss the apparent underestimate of WRF for max temperature. There appears to be ~2 deg C underestimate, which can strongly influence the Guenther estimates above 30 C.

We add a sentence to the caption and we discuss further these implications in Sect. 2.3.2.

28) Figure 4: Consider showing only those tracks with flux data.

As in response to comment 25, we want to show the full track where at least concentrations if not the flux were measured.

29) Figure 7: This figure is confusing. It seems to imply a continuous range of footprint sizes from 0 to 3500 km? Perhaps (if I understand correctly) it should be re-titled to read something like "distance along flight track". Also, why not use flux values rather than emission rates? I assume that 4 kg/hr = 1000 ug/m2-hr. For those portions of the flight track showing significant over- and under-estimates, why not be more specific with location in California and type of ecoregion(s)?

We agree that Figure 7 label might be confusing. The figure mostly served the purpose of showing overall comparison at finer scale along the tracks. The footprint is not constant but is derived for each point. We *show specific ecoregions on the next figures. We still thought it was worth leaving this figure in but in response to this and the next comment we decided to move this figure from the main manuscript to the supplement.*

30) Figure 8: As mentioned earlier, recommend strongly that all four models be compared together. It is confusing to move from ecoregion averages to footprint emission amounts.

In order to avoid confusion we deleted figure 7. All four models are compared as ecoregion averages.

31) Supplement 1: As mentioned earlier, having more descriptions of the four models would be useful. Also, more details on how the basal emission fluxes were derived from the airborne measurements would be very helpful. See "p.8, section 2.4.1" comments above.

We really appreciate all the useful comments which we have implemented where possible. This was the first comparison of these models at regional scale and we hope future progress will continue in this area. We thank the reviewer for reading the manuscript carefully and for providing many useful comments.

Anonymous Referee #2

1) Based on airborne data from flight tracks over California, this study presents the evaluation of Basal Emission Factors, derived from measurements using different landcover maps, and emission estimates, for the description of biogenic isoprene source. Land-covers considered in three different biogenic volatile organic compound emission models (BEIGIS, MEGAN 2.04 and MEGAN v.2.1) are considered for the calculation of Basal Emission Factors, and isoprene emission fluxes calculated by the CARB's hybrid model are evaluated. This manuscript is well written and focuses on a very valuable and important work which totally falls in the scope of ACP topics. Biogenic source of volatile organic compounds are indeed still only crudely quantified, and model estimates associated with a high uncertainty. Only a few studies presenting model-data comparison at a regional scale have been published so far, and I therefore both enjoyed the originality and the scientific contribution of this study and appreciated the work performed.

*We really appreciate the positive feedback and in particular the compliment on "*the originality and the scientific contribution of this study and appreciated the work performed".

2) However I strongly believe there is still a room for improvement in the presentation of this work in order to clarify the methodological approach and to present a deeper analysis of some of the results which are only quickly described. Here are some feedbacks on your manuscript and suggestions for improvements that I would really like to be considered before publication in ACP.

Definitely, we realize there is much more to accomplish in this area and we thank the reviewer for highlighting the points worth attending to. We want to stress that the particular part of the study presented in the paper did not intend to focus on the methods (which are very interesting and were developed to accomplish the study) but rather on the scientific implications which could lead to improvements of model inputs at relevant temporal and spatial resolution for regional models.

General comments:

3) The positioning and central objective(s) of this work have to be clarified, and homogenized in the manuscript. It is stated at the beginning of section 3.3 that "The primary goal of the study was to

verify the accuracy of isoprene emission estimates used by CARB (. . .) simulated by CARB's hybrid model". And yet, very little space is eventually given in the manuscript to the evaluation of CARB's hybrid model results, especially if we do not consider the sensitivity tests for temperature, radiation and LAI, which to me are not really part of a model evaluation. This evaluation is presented as an independent work in the abstract, with only a few lines dedicated, while much more room is given to the BEF evaluation. All these different aspects of the work are really valuable and interesting to me, and are all worth being presented, but with the room entitled considering the main objectives given.

The objectives are clarified in the revised version. The reviewer makes a great point that the sensitivities to input variables are not everything. We do think that the architectures of these models are quite similar and what we evaluate is the direct comparison to measured ecosystem variables. We put more emphasis on the CARB model in the revised version. We thank the reviewer very much for finding "all the different aspects of the work valuable, interesting and worth being presented".

4) The agreement between measurements and model, regarding BEF and emissions, is somewhat overstated when described as "remarkable" (section 3.2.1) and "extremely good" (section 3.3). I agree that the main characteristic depicted by the measurements are generally well captured by the model (or model parameters i.e. BEF), which is already very encouraging considering the uncertainty in biogenic VOC emission estimates generally, but several emission peaks or BEF regional variability are still not captured by the model / model parameter. The comparison of isoprene fluxes simulated by CARB's hybrid model with measurements would really benefit from a deeper analysis: what are the possible explanations for model/data disagreement regarding peak simulation, for instance? The objectives of the sensitivity tests should also be clarified: is the range of variability used for temperature/radiation representing the range of variability observed in the field? Moreover, regarding BEF especially, plots, rather than regional maps, comparing the BEF values for the same location along the different flight tracks would make the comparison analysis more visible.

We agree with the reviewer that we should allow the data speak more for themselves and not use descriptors such as extremely good or remarkable. We make a deeper insight into model agreements and disagreements. We also make it clear that the objective of the sensitivity studies was to represent the expected variability within realistic bounds.

5) It is stated, in the introduction and conclusion especially, that biogenic VOCs play a key role in California regarding air quality. What is exactly the contribution of biogenic sources to VOC emissions in this region? Please add some quantification.

We now add in the introduction: "In CARB's current emission inventory (CARB 2015), biogenic sources constitute 60% of total VOC emissions in California. Isoprene accounts for 37% of the biogenic VOC and 22% of total VOC. Furthermore, the important impacts of isoprene and other biogenic VOC emissions on total VOC reactivity, ozone formation, and aerosol formation in the Central Valley and surrounding mountains have been demonstrated in many previous studies (Kleinman et al., 2016; Worton et al., 2013; Rollins et al., 2012; Steiner et al., 2008; Dreyfus et al., 2002) pointing to the need for assessing the accuracy of emission inventories." (...) "In this work we focus on quantifying the agreement between observed and modeled isoprene emissions from its main sources as an important step leading to increased confidence in air quality predictions."

6) Introduction, page 3, line 4: please clarify and detail “as well as the preceding meteorological history”. Do you mean the past 24h or 10-days conditions for temperature and radiation, as taken into account in the MEGAN model?

Yes, we meant to draw attention to the transition from a relatively cool period to a relatively warmer period of early summer, which was responsible for the wide range of conditions. Therefore, 24 and 240 h preceding meteorological history would be more relevant than during the middle of the season.

7) Supplementary material and information are mentioned several times in the manuscript but unfortunately did not seem to be actually integrated in the supplementary document (which only presents 2 supplementary figures). So. . . either I missed a document wellhidden or some updates and corrections need to be performed. To properly understand the approach adopted for this work, it is indeed really important to find the information regarding “More methodological details” (page 8, line 15), “Further details on the application of the inverse algorithm” (page 8, line 28) and “Input variables tested” (page 9, line 21), supposed to be in a supplementary material, while Figure 8 does not seem to be part of this additional material anymore. Moreover the Figure S2, addressing the impact of fires on isoprene emissions, is indeed interesting but is not cited or used anywhere in the manuscript. I understand that supplementary information are not meant to be described in full details but at least should they be cited or used even shortly somewhere in the core of the manuscript, or deleted.

We thank the reviewer for pointing out these issues all of which are fixed in the revised manuscript. As we mentioned in response to a similar comment from Reviewer 1, the referenced text in the supplement was not transferred properly and this has now been fixed. We delete the figure showing the previous fire history in some regions containing oak woodlands.

8) Many details, sometimes bringing a bit of confusion and that could be synthesized, are given regarding the different datasets used to build the landcover maps used by the different models, but some of the differences and specificities of the models, which can affect significantly isoprene emission estimates, are not given clearly. For instance how many vegetation categories are considered by each model? How is LAI considered (grid-average or for each vegetation type) and which year or climatology is used? Adding a table summarizing all these information, together with model spatial and temporal resolutions, would really help. The CARB’s hybrid model is described in section 2.1.4 as an adaptation of MEGAN v.2.04 to include MEGAN v.2.1 enhancements. So what are the actual differences between CARB’s hybrid model and MEGAN v.2.1?

These are all very good points. In response to this and Reviewer 1 comment #12 we add a new Table 2 with a summary describing the main attributes of each model. The models use explicit emission factors which do not contain information about vegetation categories, although it is true that each of these models can have any number of PFTs as well as a specific number(s) of the default PFTs.

9) Section 3.1 and Figure 2: Landcover is shown to be a critical driving variable and yet only the oak woodland distribution is illustrated. It would be really worth and important to show the landcovers for all the different vegetation categories as well, simplified if needed depending on the number of vegetation categories, for each of the models’ landcover, and not only the calculated BEF distribution.

We appreciate this comment but we did not use any PFT categories that make up the emission factors but instead used the explicit emission factors for the specific model applications in the manuscript. We do *agree that for places other than California and for global models it is indeed important to show different vegetation categories. While we emphasize that oak woodlands are extremely high isoprene emitters dominating isoprene sources in California we do note other isoprene emitters are present such as Eucalyptus trees and other less significant sources.*

Specific comments:

10) Page 1, line 5: change “Basal Emission Factors (BEFs) distribution” to “Basal Emission Factor (BEF) distribution”.

Done.

11) Page 3, line 3: change “Large changes in temperatures” to “Large changes in temperature”.

Done.

12) Page 4, line 5: add “to” in “this can contribute TO uncertainties in isoprene emission estimates.

Done.

13) Page 5, line 4: change “modeling with 1 km2” to “modeling with 1 km^2”.

Done.

14) Page 5, line 28: change “MEGANv.2.1” to “MEGAN v.2.1”, adding space. The long name MEGAN v.2.1 landcover v.2.2 used several times in the manuscript could be shortened.

The space has been added. The long name is needed to avoid potential confusion with the version of MEGAN and landcover”.

Tables and Figures:

15) Figure 1: The list of ecoregions is very long and hardly readable, and may not need to be presented in full details. This information should therefore either be simplified or enlarged/presented differently to be fully readable. If all these categories have to be presented, they could be listed in one table given in the supplementary material for instance.

The figure legend containing specific names of the ecoregions has been enlarged and moved to the supplement.

16) Figure 2: Please check and correct the caption at this figure does not only give the “Landcovers used by the models”, as stated at the beginning of the sentence, but also BEFs. Please also detail what “dtiso+eiso” means.

The caption has been updated accordingly to describe “BEF landcovers”. dtiso and eiso are the components of BEIGIS EFs and represent isoprene emission factor for deciduous and evergreen trees, respectively. This information has also been added.

17) Figure 3 and section 2.3.2: The optimal approach regarding temperature accuracy was found to be using the 4 x 4 km WRF model nudged by CALMET or CALMET directly. This result is not illustrated in Figure 3, and should be added.

> *Unfortunately, we have not made 4 x 4 km runs for this domain which was done before the CARB's model development. However, 8 x 8 km already worked pretty well. The CALMET dataset has been, in addition, independently evaluated by CARB to ensure its accuracy. Consistently, however, the accuracy must necessarily be less good near the foothills which we have highlighted in the manuscript.*

Once again, we thank the reviewer for providing thoughtful comments which we found very useful for the improvement of our manuscript.

References:

CARB 2015, California Air Resources Board Almanac Emission Projection Data, "2015 Estimated Annual Average Emissions", published in 2013, http://www.arb.ca.gov/app/emsinv/2013/emssumcat_query.php?F_YR=2015&F_DIV=0&F_SEASON=A&SP=2013&F_AREA=CA#9 date accessed: 21 May 2016.

Dreyfus, G. B., Schade, G.W., and Goldstein, A. H.: Observational constraints on the contribution of isoprene oxidation to ozone production on the western slope of the Sierra Nevada, California, Journal of Geophysical Research: Atmospheres, 107, 2002.

Kleinman, L., Kuang, C., Sedlacek, A., Senum, G., Springston, S., Wang, J., Zhang, Q., Jayne, J., Fast, J., Hubbe, J., et al.: What do correlations tell us about anthropogenic–biogenic interactions and SOA formation in the Sacramento Plume during CARES? Atmospheric Chemistry and Physics Discussions, 15, 25 381–25 431, 2015.

Misztal, P. K., Karl, T., Weber, R., Jonsson, H. H., Guenther, A. B., and Goldstein, A. H.: Airborne flux measurements of biogenic isoprene over California, Atmospheric Chemistry and Physics, 14, 10 631–10 647, doi:10.5194/acp-14-10631-2014, 2014.

Rollins, A., Browne, E., Min, K.-E., Pusede, S., Wooldridge, P., Gentner, D., Goldstein, A., Liu, S., Day, D., Russell, L., et al.: Evidence for NOx control over nighttime SOA formation, Science, 337, 1210–1212, 2012.

Scott, K. I. and Benjamin, M. T.: Development of a biogenic volatile organic compounds emission inventory for the SCOS97-NARSTO domain, Atmospheric Environment, 37, S39–S49, doi: 10.1016/S1352-2310(03)00381-9, 2003.

Steiner, A. L., Cohen, R., Harley, R., Tonse, S., Millet, D., Schade, G., and Goldstein, A.: VOC reactivity in central California: comparing an air quality model to ground-based measurements, Atmospheric Chemistry and Physics, 8, 351–368, 2008.

Vaughan, A. R., Lee, J. D., Misztal, P. K., Metzger, S., Shaw, M. D., Lewis, A. C., Purvis, R. M., Carslaw, D. C., Goldstein, A. H., Hewitt, C. N., Davison, B., Beevers, S. D., and Karl, T. G.: Spatially resolved flux measurements of NOx from London suggest significantly higher emissions than predicted by inventories, Faraday Discussions, 10.1039/C5FD00170F, 2016.

Worton, D. R., Surratt, J. D., LaFranchi, B. W., Chan, A. W., Zhao, Y., Weber, R. J., Park, J.-H., Gilman, J. B., De Gouw, J., Park, C., et al.: Observational insights into aerosol formation from isoprene, Environmental science & technology, 47, 11 403–11 413, 2013.

Yu, H., et al.: Development of landcover and emission factors for isoprene and monoterpene emission modeling and evaluation in the southern United States using airborne direct and indirect flux measurements, in prep.

Manuscript prepared for Atmos. Chem. Phys.
with version 2015/12/14 8.00 Copernicus papers of the LaTeX class copernicus.cls.
Date: ~~2 February~~ 22 May 2016

Evaluation of regional isoprene emission factors and modeled fluxes in California

Pawel K. Misztal[1,2], Jeremy C. Avise[3,4], Thomas Karl[5], Klaus Scott[3], Haflidi H. Jonsson[6],
Alex B. Guenther[2,4,7], and Allen H. Goldstein[1]

[1]University of California at Berkeley, Berkeley, California, USA
[2]National Center for Atmospheric Research, Boulder, Colorado, USA
[3]California Air Resources Board, Sacramento, California, USA
[4]Washington State University, Department of Civil and Environmental Engineering, Pullman, Washington, USA
[5]Institute for Meteorology and Geophysics, University of Innsbruck, Innsbruck, Austria
[6]Center for Interdisciplinary Remotely-Piloted Aircraft Studies, Monterey, California, USA
[7]Department of Earth System Science, University of California, Irvine, California, USA

Correspondence to: P. K. Misztal (pkm@berkeley.edu)

Abstract. Accurately modeled Biogenic Volatile Organic Compound (BVOC) emissions are an essential input to atmospheric chemistry simulations of ozone and particle formation. BVOC emission models rely on Basal Emission ~~Factors (BEFs~~Factor (BEF) distribution maps based on emission measurements and vegetation landcover data but these critical input components of the models as well as model simulations lack validation by regional scale measurements.

We directly assess isoprene emission-factor distribution databases for BVOC emission models by deriving BEFs from direct airborne eddy covariance (AEC) fluxes (Misztal et al., 2014) scaled to the surface and normalized by the activity factor of the Guenther et al. (2006) algorithm. The available airborne BEF data from approx. 10,000 km of flight tracks over California were averaged spatially over 48 defined ecological zones called ecoregions. Consistently, BEFs used by three different emission models were averaged over the same ecoregions for quantitative evaluation. Ecoregion-averaged BEFs from the most current landcover used by the Model of Emissions of Gases and Aerosols from Nature (MEGAN) v.2.1 resulted in the best agreement among the tested landcovers and agreed within 10% with BEFs inferred from measurement. However, the correlation was sensitive to a few discrepancies (either overestimation or underestimation) in those ecoregions where landcover BEFs are less accurate or less representative for the flight track. The two other landcovers demonstrated similar agreement (within 30% of measurements) for total average BEF across all tested ecoregions but there were a larger number of specific ecoregions that had poor agreement with the observations.

Independently, we performed evaluation of the new California Air Resources Board (CARB) hybrid model by directly comparing its simulated isoprene area emissions averaged for the same flight times and flux footprints as actual measured area emissions. The model simulation and the observed surface area emissions agreed on average within 20%.

We show that the choice of model landcover input data has the most critical influence on model-measurement agreement and the uncertainty in meteorology inputs has a lesser impact at scales relevant to regional air quality modeling.

1 Introduction

Vegetation in California emits isoprene, terpenes, and oxygenated biogenic volatile organic compounds (BVOC) which react with anthropogenic pollutants to form ozone and particulate matter. Isoprene (2-methyl-1,3-butadiene) is the dominantly emitted BVOC globally (Guenther et al., 2012; Sindelarova et al., 2014) and the single most important species affecting regional air quality in most regions (Unger et al., 2013; Müller et al., 2008; Henze and Seinfeld, 2006; Rosenstiel et al., 2003) including California. In CARB's current emission inventory (CARB, 2015), biogenic sources constitute 60% of total VOC emissions in California. Isoprene accounts for 37% of the biogenic VOC and 22% of total VOC. Furthermore, the important impacts of isoprene and other biogenic VOC emissions on total VOC reactivity, ozone formation, and aerosol formation in the Central Valley and surrounding mountains have been demonstrated in many previous studies (Kleinman et al., 2015; Worton et al., 2013; Rollins et al., 2012; Steiner et al., 2008; Dreyfus et al., 2002) pointing ~~to the~~ need for assessing the accuracy of emission inventories.

Based on previous BVOC emission measurements from Californian oak woodlands, which were made exclusively at branch and leaf levels (e.g. Winer et al., 1992), the vast majority of California's isoprene emissions are expected to occur from oak trees and to some extent from Eucalyptus trees. The dominant oak environments in California are located in the foothills encompassing the Central Valley and along the Pacific Coast Ranges. Previous studies have shown that estimation of biogenic emissions is uncertain because of the lack of regional-scale measurements and differences in driving input variables as well as the way the model components are calculated. Guenther et al. (2006) and Arneth et al. (2011) presented the sensitivity of BVOC emission estimates to landcover and weather/climate variables. Other parameters related to the driving inputs such as spatial (Pugh et al., 2013) or temporal (Ashworth et al., 2010) resolutions have also been shown to impact MEGAN model performance. Situ et al. (2014) performed a detailed study of the importance of input variables and parameters on emissions simulated by the MEGAN model using a Monte Carlo approach and suggested that large uncertainties of emission estimates can be reduced if emission factor, photosynthetically active radiation (PAR) and temperature input accuracies are improved. There are currently no algorithms for modeling accurately the emission response to stresses (e.g. water stress) which requires further mechanistic understanding of biogenic emissions and more ecosystem-scale measurements (Potosnak et al., 2014).

Despite the knowledge of complexities behind accurate modeling, without regional measurements there is no reliable means of verifying whether modeling simulations of biogenic emissions and air quality work well across the specific regions. Recently, direct airborne eddy covariance (AEC) measurements based on continuous wavelet transformation have become a valuable tool for quantifying emission sources and sinks of atmospheric reactive gases (Misztal et al., 2014; Yuan et al., 2015; Wolfe et al., 2015) and these types of measurements are uniquely valuable for validation of the regional biogenic emission models and landcover emission factor driving inputs.

The California Airborne BVOC Emission Research in Natural Ecosystems Transects (CABERNET) study was conducted in early summer 2011 to directly measure for the first time the regional scale BVOC emissions using an aircraft with one of the goals being evaluation of the performance of the emission models used by California Air Resources Board (CARB) in simulating state-wide air quality. Eight research flights were conducted including mostly horizontal transects (Misztal et al., 2014) to measure the regional emissions over the majority of oak woodland regions in California at a 2-km spatial resolution.

In addition, stacked gradient profiles were flown at multiple altitudes to measure vertical flux divergence (Karl et al., 2013) allowing scaling of aircraft-level flux measurements to ground-level emissions (surface emissions). We flew most extensively over areas identified as code 6 (Central California Foothills and Coastal Mountains) in the level III United States Environmental Protection Agency (USEPA) ecoregion classification(USEPA, 2014) (see USEPA ecoregion map in Figure 1). The 29 sub-ecoregions (level IV) of the level III ecoregion 6 comprise oak woodlands which were confirmed to be dominant isoprene emission sources with effective measured basal emission factors (BEFs) of more than 4 mg m^{-2} h^{-1} and occasionally up to around 10 mg m^{-2} h^{-1} (Misztal et al., 2014). Large changes in ~~temperatures~~ temperature (and radiation) during the field campaign as well as the preceding meteorological history (from day to day, and over a week as the early summer season was becoming warmer) were responsible for a broad range of observed emissions from less than 1 mg m^{-2} h^{-1} on a cool day to about 15 mg m^{-2} h^{-1} (or more) on a hot day over a densely populated oak area (Misztal et al., 2014).

~~Here we~~ In this work we focus on quantifying the agreement between observed and modeled isoprene emissions from its main sources as an important step leading to increased confidence in air quality predictions. We use our previously published direct airborne flux measurements to infer isoprene BEFs (referred to as measured BEFs) to evaluate emission factors based on landcovers (referred to as landcover BEFs) used by the three models typically applied in California: 1) Biogenic Emission Inventory processing model (BEIGIS) (Scott and Benjamin, 2003), 2) Model of Emissions of Gases and Aerosols from Nature (MEGAN) v.2.04 (Guenther et al., 2006), and 3) MEGAN v.2.1 (Guenther et al., 2012). Independently, we evaluate performance of the new California Air Resources Board (CARB) model (MEGAN v.2.04 and BEIGIS hybrid which included enhancements from MEGAN v.2.1) by directly comparing simulated isoprene area emissions averaged for the same flight times and flux footprints as actual measured area emissions.

2 Methods

2.1 Modeling approaches

Modeling of BVOC emissions involves a framework including emission factors, short-term and long-term emission algorithms and a canopy environment model (a model to relate above canopy environment to leaf level conditions), along with data bases of landcover and meteorological driving variables.

Different models use often different inputs to simulate isoprene emissions and each model is characterized by its specific architecture (see Table 1). The following models are commonly used for simulating biogenic emissions in California: 1) BEIGIS (CARB's original biogenics model) using the US Geological Survey's Gap Analysis Project (GAP) landcover database to quantify coverage of oaks and other species composition (Scott and Benjamin, 2003; Davis et al., 1998), 2) MEGAN v.2.04, landcover v.2.1 (Guenther et al., 2006) based on WestGAP landcover database and Forest Inventory and Analysis (FIA) National Program, and 3) MEGAN v.2.1, landcover v.2.2 (Guenther et al., 2012) – based on the National Landcover Dataset (NLCD, Homer et al.(2004)), FIA, and plant functional type (PFT) datasets.

MEGAN v.2.1 model provides the most current and accurate landcover, but the model architecture is not significantly different from MEGAN v.2.04 for isoprene. BEIGIS model shares MEGAN v.2.04 architecture but uses different landcover and vegetation specific emission factors. Following the CABERNET measurements, further enhancements from MEGAN v.2.1. were adopted by CARB resulting in a development of a hybrid BEIGIS/~~MEGANv~~MEGAN v.2.04/v.2.1 model designed for regional simulations, and its statewide emission estimates of isoprene are evaluated here with CABERNET measured AEC fluxes.

The three model architectures are extremely similar because they evolved from the same roots. Differences between the model outputs occur mainly due to differences in the landcover driving variables (plant species composition, leaf area index (LAI)) and meteorological driving variables (light, temperature). When comparing different models with observations, it is important to first determine the effects of different input variables that are used and perform extensive sensitivity studies. The resolution and evaluation of these driving variable databases is particularly critical in the areas close to the mountains that typically have high gradients of temperature and vegetation and where meteorological stations may not be as densely spaced compared to near the urban areas or where gradients in temperature are smaller. Since the models predict that the major isoprene source regions in California are predominantly oak savannas in the foothills where temperature estimates are uncertain, this can contribute to uncertainties in isoprene emission estimates.

To evaluate the accuracy of the landcover used as the basis for the models' emission factor distributions, we used the 2-km resolution measured flux data normalized for temperature and PAR according to the Guenther et al. (2006) algorithm to derive airborne BEFs. The inverse emission algorithm approach has been used earlier at a canopy scale (Misztal et al., 2011) and recently to derive BEFs from satellite measurements of formaldehyde (Marais et al., 2014). To evaluate the meteorological driving variables, we compared hourly temperature data simulated by the Weather Research and Forecasting (WRF) model (Skamarock et al., 2005) at a 4x4 km resolution with available weather station data along some of the CABERNET flight tracks. For the fair comparison in this paper, we have not set any model's emission factors to measured emission factors.

2.1.1 BEIGIS

The Biogenic Emission Inventory processing model (BEIGIS) (Scott and Benjamin, 2003) was developed by CARB as a regional model specific to California, and is spatially resolved at 1 km^2 and temporally at 1 hour. BEIGIS uses California landcover, leaf mass, and emission rate databases with a geographic information system (GIS)~~, is a regional model specific to California, and is spatially resolved at 1 km^2 and temporally at 1 hour~~. The initial set of BEIGIS inputs includes GIS-based maps of landcover types. They are based on a USGS Gap Analysis Project (GAP) biodiversity database which covers natural areas of California (Scott et al., 1993; Davis, 1994; Karlik et al., 2003). The database was generated from summer 1990 Landsat Thematic Mapper satellite images, 1990 high altitude color infrared imagery, vegetation maps based on historical field surveys, and other miscellaneous vegetation maps and ground surveys. The urban and crop areas are not represented by the GAP database and use independent maps. These maps are subsequently used to assign mostly branch-scale emission factors which in the case of GAP covered areas come from a compilation by Benjamin et al. (1996) and a specific leaf weight (to convert LAI to biomass density) database (Nowak et al., 2000). The landscape emission factor layers are subsequently formed and are used with environmental correction algorithms Guenther et al. (1993); Harley et al. (1998) using hourly temperature and solar radiation datasets gridded at 4 km^2. A canopy environment model is not used in BEIGIS, and it is assumed that the branch-scale emission factors account for shading and canopy environment effects. The model has many similarities to the predecessor of the MEGAN model (Guenther et al., 1993, 1995) since it is using similarly derived emission factor maps (GAP/FIA, branch-scale emission factors) and a similar framework for application of light and temperature algorithms, except that the BEIGIS model was specifically optimized for California. This includes using an 8-day LAI and phenology database, where specific phenology masks are applied to deciduous trees and shrubs, grasses and herbaceous plants to turn on and off their emissions at different times of year, while evergreen trees and some shrubs are assumed to have emissions all year.

2.1.2 MEGAN v.2.04

The Model of Emissions of Gases and Aerosols from Nature (MEGAN) v.2.04 (Guenther et al., 2006) was used in the initial stages of our study to plan CABERNET flight tracks and was also tested in the early stages of measurement model comparisons using the observed airborne BEFs. MEGAN is designed for both global and regional emission modeling with 1 ~~km2~~ km^2 spatial resolution. This version of MEGAN defined emission factors as the net flux of a compound into the atmosphere which was intended to account for losses of primary emissions on their way into the above canopy atmosphere. The model uses an approach that divides the surface of each grid cell into different Plant Functional Types (PFTs) and non-vegetated surface. The PFT approach enables the MEGAN canopy environment model to simulate different light and temperature distributions for different canopy types (e.g., broadleaf trees and needle trees). In addition, PFTs can have different LAI and leaf age seasonal patterns (e.g., evergreen and deciduous). MEGAN v.2.04 accounts for regional variations using geographically gridded databases of emission factors for each PFT. The standard MEGAN global classification included 7 PFTs, but for regional modeling a classification scheme can have any number of PFTs.

2.1.3 MEGAN v.2.1

The MEGAN v.2.1 model (Guenther et al., 2012) includes enhancements to MEGAN v.2.04. The main architecture of the model is very similar (see the Supplement Fig. ~~S1~~S2) but there are several significant differences in how emission factors are represented, deposition to the leaf surface accounted for (relevant for species such as methanol but not isoprene), more generic PFTs are used for global modeling, and most importantly a new landcover database (v.2.2) is included that was derived by combining high resolution imagery (60 m, and 30 m) with species composition data. The base MEGAN v.2.1 landcover v.2.2 includes more than 2000 ecoregions, which allows for the emission factor for a given PFT (e.g. temperate needleleaf trees) to change as a function of ecoregion. The MEGAN landcover product is further described in “Landcovers” section below. While the previous version of MEGAN (v.2.0) defined emission factors as the net flux of a compound into the atmosphere, the MEGAN (v.2.1) emission factor represents the net primary emission that escapes into the atmosphere but is not the net flux because it does not include the flux of chemicals from the above canopy atmosphere down into the canopy. Emission factors based on scaled up leaf level emissions inherently exclude the deposition component. In order to use above canopy flux measurements to establish emission factors, an estimate of the deposition flux is added to the above canopy flux measurements to determine the MEGAN v.2.1 emission factors. For isoprene this deposition flux estimate is equal to zero.

2.1.4 CARB's hybrid model

The MEGAN v.2.04 model framework was adapted at CARB to include ~~MEGANv~~MEGAN v.2.1 enhancements such as 8-day LAI (as opposed to monthly average LAI), longer-term (10-day) temperature and PAR impacts on the emission (consistent with Guenther et al. (2006) algorithm), and many of the California specific datasets developed in conjunction with the BEIGIS model. For this study, the model was run at 2 km x 2 km resolution and driven by meteorology at 4 km x 4 km. The LAI data used was the 8-day MODIS LAI for 2011. ~~This~~ In preliminary runs (not shown), this regional model most closely agreed with the measured fluxes and is also currently used by CARB to estimate the BVOC emissions inventory for California. However, the model has not been calibrated on the measurement data to ensure that the comparison is fair. While we show BEF comparison for all three model's landcovers, we narrow our model comparison to the CARB's hybrid model. In this application of MEGAN (v.2.04), the model produced hourly emissions estimates at a 2 km x 2 km resolution. To facilitate the model – measurement comparison, the hourly emission estimates were interpolated to the measurement time stamps and the modeled flux was calculated in a GIS environment as follows: 1) convert the grid cell emission rates to areal fluxes; 2) calculate the area weighted average flux (based on intersecting the grid with the flux footprint); and 3) convert the area weighted flux to an emission rate by multiplying by the calculated footprint area.

The flux footprint corresponding to each aircraft measurement is calculated as the half-width of the Gaussian distribution, which accounts for 90% of the total flux. In order to account for the remaining 10% of the flux, an additional 10% is added to the simulated area weighted emissions.

2.2 Model domain and ecoregions

The CABERNET flights covered a large portion of California including representative areas with high densities of oak trees which are expected to dominate the statewide isoprene emissions. Ecoregions denote areas of general similarity in ecosystems and in the type, quality, and quantity of environmental resources (Griffith et al., 2008).

A map of California ecoregions overlaid with the CABERNET flight tracks (shown earlier in Figure 1) provides information on the extent of their spatial coverage with respect to airborne measurements. Most of the subecoregions (level IV) belonging to the ecoregion 6 (level III:Central California Foothils and Coastal Mountains) denoted in yellow were covered, as well as some subecoregions of the ecoregion 7 (Central California Valley) in brown, ecoregion 5 (Sierra Nevada) in green, and ecoregion 14 (Mojave Basin and Range) in pink. Of the 48 subecoregions flown over during the CABERNET campaign, 29 subecoregions were within ecoregion 6 which comprises most of the oak woodlands in California.

The primary distinguishing characteristic of ecoregion 6 is its Mediterranean climate of hot dry summers and cool moist winters, and associated vegetative cover comprised mainly of isoprene emitting oak woodlands. Ecoregion 6 also includes non/low- isoprene emitting chaparral and grasslands which occur in some lower elevations and patches of pine are found at the higher elevations. Surrounding the lower and flatter Central California Valley (ecoregion 7), most of the region consists of open low mountains or foothills, but there are some areas of irregular plains and some narrow valleys. Large areas in ecoregion 7 are used as ranch lands and grazed by domestic livestock. Relatively little land in this ecoregion has been cultivated, although some valleys are major agricultural centers such as the Salinas area or the wine vineyard centers of Napa and Sonoma. Natural vegetation includes coast live oak woodlands, Coulter pine, unique native stands of Monterey pine in the west, and blue oak, black oak, and grey pine woodlands to the east (USEPA, 2014).

2.3 Driving inputs

2.3.1 Landcovers

The landcover used to drive the model has a critical influence on model performance because it defines the type of vegetation or plant function type (PFT), land fraction, and finally determines the emission factor. Up-to-date landcover products should give more accurate results because the landcover can change due to growing and senescing vegetation, fires, and land-use change or plant species composition change. The airborne flux measurement-model comparison provides an opportunity to identify any inaccuracies in landcover databases which can then be used to improve them. Landcovers used by the models in this study are presented in Figure 2.

The Gap Analysis Program (GAP) database can be used to construct the spatial distribution of oak woodland areas (Figure 2a). This distribution is extremely similar to the BEIGIS emission factors (Figure 2b) which were based on the GAP data. While the global MEGAN v.2.04 landcover v.2.1 (Figure 2c) was also based on FIA and WestGAP datasets and interestingly showed almost identical BEF means for isoprene compared to BEIGIS isoprene BEFs, the standard deviations of spatial variability were much different with BEF distribution that were more smoothed out across many areas of California. The latest MEGAN v.2.1 landcover v.2.2 (Figure 2d) is a state-of-the-art product which showed the most accurate match with airborne fluxes. This landcover is based on a high resolution (60 m) PFT database using the Community Land Model 4 (CLM4) PFT scheme generated for the US for the year 2008 and is available with the MEGAN v.2.1 input data (http://bai.acd.ucar.edu/MEGAN/) (Guenther et al., 2012). The database was created by combining the National Landcover Dataset (NLCD, Homer et al. (2004)) and the Cropland Data Layer (see http://nassgeodata.gmu.edu/CropScape/), which are based on 30-m LANDSAT-TM satellite data, with vegetation species composition data from the Forest Inventory and Analysis (www.fia.fs.fed.us) and the soil database of the Natural Resources Conservation Services (http://sdmdataaccess.nrcs.usda.gov/). The processing included adjusting the NLCD tree cover estimates in urban areas to account for the substantial underestimation of the LANDSAT-TM data (Duhl et al., 2011). The California Information Node (CAIN) database from the UC Davis repository (http://ice.ucdavis.edu/project/cain) contains exactly the same habitats as the GAP database but was independently derived. The CAIN database augmented several datasets linked to the National Biological Information Infrastructure (NBII) which was linked to the California Department of Forestry and Fire Protection (CalFire) Fire and Resource and Assessment Program (FRAP). This database was also based on the FIA, and complements the GAP database, in particular in southern CA. The northwest region of CA is more extensively represented by GAP. Combination of the GAP and CAIN dataset therefore is useful in the context of BVOC emission modeling in California.

2.3.2 Temperature and radiation

Hourly temperature data were simulated by WRF at 4 km x 4 km resolution. Based on comparison with weather station close to gradient stacked profile in RF6 and RF7, we found that WRF spatial resolutions lower than 8 km x 8 km can lead to temperature inaccuracies of more than 3 ºC during peak periods (Figure 3). Similar conclusions were made by Yver et al. (2013). ~~For~~ Even at 8 km x 8 km resolution, occasional discrepancies up to 2 °C were noted. Although we did not include 4 km x 4 km resolution to this comparison, it is expected that the accuracy would further improve. Taking 2 °C as an upper limit of uncertainty would result in a potential bias of up to 20% to the emission factors (overestimation) and modeled fluxes (underestimation). However, lower bias would be expected further inland where temperature gradients are less steep, the coverage of meteorological stations is higher, or when temperature is outside of the daily maximum. For additional validation of WRF temperature data a diagnostic meteorological model (CALMET) was used by CARB. Despite mostly good agreement, areas were identified with large discrepancies. Since CALMET interpolates in 2D the temperature surface from the available met stations, inaccuracies may be expected in areas were stations are not densely represented. The optimal approaches for California were found to be the 4 x 4 km WRF model nudged by CALMET or CALMET directly. The dynamics of the temperature changes close to the foothills during a day can be seen on the animation (http://bit.ly/wrftempcabernet) where gradients are very high.

Photosynthetically Active Radiation satellite datasets were recently validated by Wang et al. (2011) and Guenther et al. (2012). The CARB's model (adapted MEGAN application) used the WRF insolation directly. The uncertainty in the PAR data is expected to be less prone to spatial differences relative to temperature and also will be small because we chose the flight days to be completely cloudless. Potential uncertainty in PAR can still be due to averaging and aerosol loadings. Nevertheless, we assume that the relative bias due to PAR should be well below 10% at 4 km x 4 km resolution and midday conditions during CABERNET.

2.3.3 LAI

The LAI dataset used was the current LAI from MODIS for the flight days and CARB's LAI data was the Terra/Aqua combined 8-day product.

2.4 CABERNET direct flux dataset

Detailed description of the campaign's 8 research flights (RFs) can be found in Karl et al. (2013) and Misztal et al. (2014). The airborne fluxes which were reported in Misztal et al. (2014) were subsequently processed using the inverse of the Guenther et al. (2006) algorithm (Eq. 1) into: 1) airborne Basal Emission Factors (BEFs) and 2) spatially averaged gridded emissions using the flux footprints. More methodological details are provided in the Supplement.

2.4.1 Application of inverse G06 algorithm to the airborne fluxes

Comparison of the measured fluxes to the model emission potentials was done after calculating BEFs from the measurements. The raw data undergoes the following workflow to obtain airborne BEFs from the airborne fluxes: 1) Application of wind corrections from “Lenschow maneuvers”; 2) Derivation of airborne concentrations from daily calibrations; 3) Wavelet and FFT flux derivation at aircraft altitude; 4) Interpolation of fluxes at aircraft altitude to the surface fluxes using coefficients from racetracks, and the ratio of the altitude above the ground (z) to planetary boundary layer depth (zi) (i.e. accounting for flux divergence); 5) Spatial averaging of surface fluxes to 2 km resolution; and 6) Derivation of BERs by normalization of the surface fluxes using surface temperature and PAR according to MEGAN algorithm which accounts for previous temperature and PAR history (equation from Misztal et al. (2011)):

$$\mathrm{BEF}_{\mathrm{AEC}} = \frac{F_{\mathrm{AEC}}}{\gamma_{T,\mathrm{PAR}}}, \tag{1}$$

where BEF is airborne basal emission factor, and $\gamma_{T,\mathrm{PAR}}$ is the Guenther et al. (2006) algorithm’s activity factor which accounted for temperature (T) and PAR of the current hour, as well as the T and PAR averaged over the previous 24 and 240 hours. ~~Further details on the application of the inverse algorithm~~

Each of the 1-5 steps represent specific uncertainty which propagates to final airborne emission factor. The uncertainties relataed to steps 1-5 have been explained in Misztal et al. (2014). In general the uncertainty due to calibration of concentration is relatively small but the largest error comes from the random error due to short-term variability which is dependent on the averaging scales. We have determined that the total error is lower than 30% for long segments (e.g. averaged over 40 km). While the random error to an individual point at 2 km must be higher (e.g. 100%), we overcome this error by spatial averaging for entire ecoregions, but take into acount only those ecoregions where the track coverage was more than 40 km. Still we find it valuable to show how the comparison looks at 2 km even though we do not evaluate these factors at these short scales. Additional source of uncertainty (step 6) is due to temperature and PAR datasets which are used in inverse Guenther algorithm. Because the response to these inputs is exponential, even a small error in these variables is further amplified. The expected accuracy +/- 2 °C and 50 μmol m^{-2} s^{-1} in these variables results in 20% of additional uncertainty propagating to emission factors. Following Gaussian propagation of errors the reported uncertainty of BEFs scaled over ecoregions is less than 40%. Unlike the area emissions reported later, the BEF approach is independent of footprint derivation and complements the analysis.

Further details including the full algorithm equation can be found in the Supplement.

2.4.2 Flux footprint application

The footprint for each flux point was derived using the Weil and Horst (1992) approach and depends on the wind speed, relative altitude to the PBL height, and the convective velocity scale. Here we use scaling developed for the mixed layer according to:

$$dx_{0.5} = 0.9 \cdot \frac{u \cdot z_{\mathrm{m}}^{2/3} \cdot h^{1/3}}{w^{*}}, \tag{2}$$

where $dx_{0.5}$ is the half width of the horizontal footprint, u the horizontal windspeed, z_m the height above ground, h the PBL height and w^* the convective velocity scale which is derived from the wavelet heat flux in each transect.

The source contribution area can be approximated by projecting an upwind-pointed half dome with the ~~dx0.5~~ $dx_{0.5}$ parameter representing a radius of that half dome. As an example this leads to a footprint of 3.1 km for ~~h~~h=2000 m, ~~zm~~z_m=1500 m, ~~u~~ u = 3.5 m/s and ~~w*~~ w^* = 1.7 m/s encountered during RF6. The upwind fetch was on the order of 12 km for RF6 and RF7. The footprint is represented by the half-widths which can be regarded as a distance between the points of the Gaussian curve where the flux falls to the half of its maximum. Therefore, the flux contribution is not the same within the halfwidth. The area of such a footprint is approximately 90% of the flux contribution relative to the entire footprint (the full Gaussian). This approximation assumes a symmetrical footprint, but in reality the footprint area is larger along the direction that the wind is blowing. The half-dome footprint approach projects the entire footprint area in the upwind direction. The example of this approach was presented in (Misztal et al., 2014, SI Fig. S5) . While this unidirectional footprint improves short-scale spatial match accuracy in occasional areas (e.g. where fraction cover was distinctly different), overall it gave very similar results to the "full-dome" approach which projects the same area symmetrically around the aircraft. This is easier to apply in the modeling environment used by CARB and therefore was implemented in this study. Recently footprint approaches for short-scale spatial comparisons have been evaluated and parametrized by Vaughan et al. (2016) .

3 Results and discussion

3.1 Landcover - a critical driving variable

The driving variables used in the models are much more important for prediction accuracy than the different model architectures. This observation is consistent with reports comparing different process-based models which differ in the modeling framework but give similar estimates when exactly the same input variables are used (Arneth et al., 2011). For example, Ashworth et al. (2010) used MEGAN to evaluate how sensitive isoprene emissions are to different time resolutions of the input data and showed that even a 70% underestimation can result from using overly coarse data. Detailed descriptions for each of the input variables tested are shown in the Supplement. We draw particular attention to landcover emission factors used by the MEGAN v.2.04, MEGAN v.2.1 and BEIGIS models, because they showed significant regional discrepancies despite having similar state-wide averages. To demonstrate where exactly these quantitative differences exist, the emission factors from landcovers used by BEIGIS and MEGAN v.2.04 were subtracted from the most current landcover used by MEGAN v.2.1 which served as a reference (Figure 4). The green areas in Figure 4 denote those areas where absolute agreement between the landcover BEFs was within ±0.5 mg m^{-2} h^{-1}. These areas occupy more than half of California, but they are mostly where absolute isoprene emission strengths are low (Central Valley, Mojave Desert, etc.). The largest negative differences for both MEGAN v.2.04 and BEIGIS landcovers are observed in the oak woodland areas surrounding the Central Valley of California. The BEIGIS landcover highest emission factors are correctly concentrated over the oak bands but their absolute magnitude was higher than in MEGAN v.2.1 landcover with differences sometimes exceeding 10 mg m^{-2} h^{-1}. In contrast, the MEGAN v.2.04 landcover had positive differences in the Sierra Mountains and close to the coast. The distribution of maximal emission factors is often offset in the models as in the MEGAN v2.04 landcover where BEFs are more smoothly dispersed and extend over part of the Central Valley as well as in the coniferous areas on the mountains where isoprene should be low. This is again in contrast to BEIGIS landcover where the BEFs change more sharply from very low to very high and vice versa. These landcovers are later quantitatively compared with airborne BEFs.

3.2 Comparison of MEGAN v.2.1 landcover v.2.2 BEFs to airborne BEFs

3.2.1 2-km BEFs

Isoprene emission model estimates were based on landcover basal emission factors, landcover distributions, and the changes in emission associated with the environmental parameters temperature and PAR. Measured AEC fluxes scaled to the surface and normalized for temperature and radiation using the Guenther et al. (2006) activity factor to derive airborne BEFs were directly compared to emission factors used by the three different models. A spatial map of measured BEFs at 2 km was overlaid over BEFs from the latest MEGAN v.2.1 landcover v.2.2 (Figure 5).

This comparison approach has some uncertainty due to the temperature and PAR datasets and the algorithm used for calculating the activity coefficient, which are much larger than the uncertainty of the measured surface fluxes because of high sensitivity to errors in temperature and PAR. However, this approach is useful because we can compare the measured BEF (essentially the measured emission potential for that ecosystem) to the BEF used to drive the model for that ecosystem. The spatial comparison clearly shows a ~~remarkable~~ close correspondence between airborne BEFs derived at 2 km spatial resolution with landcover BEFs at a similar resolution. The transition from the low emitting environment in the Central Valley to highly emitting areas occupied by oak woodlands is clear. The most accurate matches can be seen, for example, in the central part of the Sierra foothills and on the southern Coastal Range, to the south east of Monterey Bay and in the oak savannas near San Francisco Bay (East Bay hills, and Diablo Valley). The BEFs decline to zero over water bodies (e.g. San Francisco Bay, or lakes in the central-northern Sierras). There are some areas which do not agree well, for example, in the north-east over the Sierras which is dominated by conifers where airborne BEFs were somewhat lower than predicted. On the other hand, there are areas where the aircraft observed higher BEFs (e.g. beginning of the Central Coastal Range track south of the Monterey Bay in the 6ag ecoregion) that are most likely related to inaccuracies in the oak landcover database and to a lesser degree could come from potential PAR/temperature bias.

3.2.2 Eco-region specific evaluation of BEFs

California landscapes differ sustantially in plant species composition, plant functional types, and fractional coverage of vegetation. It therefore makes sense to look at model-observation comparisons separately for distinct ecological zones. We flew over 48 distinct subecoregions (level IV) which constitute more than a quarter of California ecoregions covering 120,000 km^2 which is 29% of the area of California. These subecoregions are nested within 4 broader ecoregions (level III). Ecoregion 6 comprises most of the oak woodlands in the Central California Foothills and Coastal Mountains, and we flew over 29 of its 44 subecoregions (6a-6ar). Ecoregion 7 is characterized by very low isoprene emission potential and includes most of the

Central California Valley, and we flew over 14 of its subecoregions. We also transected 2 subecoregions of the Sierra Nevada (ecoregion 5) and 3 of the Mojave Basin and Range (ecoregion 14).

The measured isoprene BEFs were much higher over ecoregions 5 and 6 than over ecoregions 7 and 14. Within ecoregion 6's subecoregions there was significant variability of BEFs ranging from near zero to above 10 mg m^{-2} h^{-1}. The BEFs from the MEGAN v.2.1 landcover v.2.2 in most cases fell in the same range as measured BEFs, but in some cases they were higher. The landcover BEF means are the averages of the entire area of each ecoregion while measured BEFs represent only the part of those areas where CABERNET flights were done. This could be particularly important for the Sierra foothills where the footprint was often overlapping with the less dense portions of the oaks in the lower part of the foothills, and therefore may not be representative of the subecoregion average. Comparison of the measured versus modeled emissions integrated over the same flux footprint areas are shown later. Nevertheless, this BEF comparison is independent of the footprint calculation and is indicative of the relatively good agreement we observed between measured and modeled isoprene emissions for most ecoregions.

Using a scatter plot of average modeled versus measured BEFs (Figure 6), it is possible to assess if the model's landcover input does a reasonable job over each of these different ecoregions. MEGAN v.2.1 Landover v.2.2 resulted in the smallest number of outlying ecoregions and overall showed the best fit.

Statistics needs to include the outliers but it is interesting also to evaluate the influence of outliers on the fits of the measured BEF with each model. Inaccuracies in the landcover can be responsible for estimates of no emissions when trees are present or high emissions where trees are not present. These cases significantly affect the overall standard regression but the robust regression which uses bisquare weights gives a smaller weight to outliers and a higher weight to the points which are closer to the regression model. The MEGAN v.2.1 Landcover v.2.2 BEFs showed reasonable agreement for most ecoregions ($r_{\text{standard fit}}$=0.62, $r_{\text{bisquare fit}}$=0.89, slope 1.08 and no offset). The remaining ecoregions occur more or less equally in the region of model overestimation or underestimation. Overall the model BEF agrees with observed BEF within 10% which is substantially better than the stated 50% model uncertainty and the 20% measurement uncertainty that we estimated. The BEIGIS model BEFs are shown for comparison and they had good agreement for a smaller number of ecoregions and in many cases either significantly overestimated or underestimated the BEFs. However, overall the fit suggested about 30% of overestimation in BEFs and a small negative offset.

Interestingly, MEGAN v. 2.04 Landcover v.2.1 BEFs were characterized by similar total averages as MEGAN v.2.1 Landcover v.2.2 BEFs, but because of the smooth distribution of the BEF had fewer ecoregions matching measured BEFs as exactly as the other two landcovers although the discrepancies were also smoother with no extremes. The slope is only 0.56 but this is compensated by a very large positive offset of 1.35 mg m^{-2} h^{-1}. As a consequence, the small BEF regions show overestimation of BEFs (e.g. in the Central Valley) but the high BEF regions tend to overestimate BEFs. In this case, the robust goodness of fit was not dramatically improved as was the case in the other two landcovers which had a much larger subset of ecoregions with explained variance. This comparison shows that each landcover could work relatively well for a global model, but clearly the latest landcover is most suitable for regional modeling. In any case, poorer agreement is expected for ecoregions where flight coverage was low or with extreme heterogeneity.

3.3 Comparison of CARB's hybrid model with CABERNET emissions

The primary goal of the study was to verify the accuracy of isoprene emission estimates used by CARB. For this reason, the emissions were simulated by CARB's hybrid model for exactly the same times and areas matching the CABERNET flux footprints to be compared with analogous 2-km measured emissions. Out of numerous simulations which were conducted between 4 km x 4 km and 1 km x 1 km resolutions and different footprint approaches, the best model-observation agreement was achieved for the 2 km x 2 km resolution and the most accurate footprints based on wavelet heat flux, wind speed and the ratio of altitude above the ground to planetary boundary layer depth (z/zi). In this paper we use non-directional symmetrical footprints. Upwind half-dome oriented footprints could be a better spatial approximation but are less practical in terms of the application to the existing CARB's modeling infrastructure. We determined that the full-dome approach we use for the homogenous oak woodlands should be similarly accurate except for a few areas at the boundaries of the oak woodland fetch or if there is a drastic inhomogeneity in landcover as indicated later in the analysis.

~~In Figure 7, the time series of simulated and measured emissions are shown to be generally in extremely good agreement (plotted along the complete flight tracks). Local discrepancies are observed in specific areas along the flight track and are discussed further in the next sections.~~

3.3.1 Sensitivity results

Modeled emissions are subject to uncertainties in the driving variables (temperature, PAR, LAI), so we performed sensitivity analyses to estimate their effect on the simulations. The objective of the sensitivity studies was to examine these effects overall and in particular to assess the degree to which a local discrepancy can be explained by uncertainty or unaccountable variability of the tested input variables. The sensitivity runs were chosen to represent the variability within realistic bounds.

Temperature

A ±20% sensitivity analysis was done for the temperature input and showed that the measured emissions were within the range of modeled emissions for most of the dataset. The temperature dependence of isoprene emissions is exponential so the highest sensitivity is expected for higher temperatures. For example, at 20 °C 20% would correspond to a 4 °C difference while at 30 °C to a 6 °C difference. Because of the exponential character a 20% change in temperature could lead to changes in emissions as large as 100% above 30 °C. The highest errors in temperature used for simulations would be likely to occur in the areas close to the mountains where large gradients of temperatures (on the order of 10 °C) occur on the order of a few km and shift spatially during a day. Nevertheless, these sensitivity runs have not found significant deviations in the expected areas of Sierra foothills which could be due to relatively low temperature when emissions are less sensitive. As the estimated uncertainty in temperature of up to 2 °C was much lower than the sensitivity used, it seems that this input could be important at short-scales but overall was not likely the most critical.

PAR

Similarly, a ±20 % sensitivity analysis for the PAR input was tested in the model simulations. The resulting range of emissions was narrower than in the case of temperature sensitivity but the general picture was similar. A systematic offset in

PAR (or temperature) would not improve significantly the generally ~~excellent~~ good agreement, but it could improve or worsen the local agreement. For the cloudless skies during CABERNET it is unlikely that inhomogeneities in the spatial distribution of PAR could be significant although there could be an impact from an aerosol haze layer or high clouds in some areas.

LAI

The LAI and the cover fraction of oak woodlands can vary greatly in the Sierra foothills and it is expected that the LAI products from MODIS may not work ideally for oak landscapes. The MODIS LAI product is an average of all vegetation at a location and so would not discriminate for example between oak trees and grasses that occur together in oak woodlands. A ±50% uncertainty in LAI is therefore not unrealistic, thus we apply this uncertainty to the model and compare with the measurements. This range in LAI resulted in relatively small changes in modeled emissions although occasionally substantial sensitivity to LAI was observed (even up to a factor of 2) but with no constant systematic offset. It is therefore assumed that the LAI used in the simulation was sufficiently accurate. The occasional model overestimations or underestimations were likely less related to the temperature (or LAI or PAR) than to the landcover inhomogeneity and inaccuracy.

3.3.2 Regional model performance over ecoregions

To test the regional performance of the model, the data have been grouped over ecoregions and the resulting variabilities are shown independently for each of these ecoregions in ~~the Supplement Figure 8.~~ Figure 7. The direct comparison of measured vs modeled fluxes suggests agreement is ~~remarkably~~ rather good in most cases not only for the midrange from the statistical distribution but also in the case of episodic spatial events (e.g. see 6ai, 6b, 6r, and 6z). The direct flux comparison agrees generally quite well as with the BEF comparison approach earlier presented, but a few exceptions are apparent such as for 6ao and 6h. These two subecoregions showed the highest discrepancy between the model and measurement but these two ecoregions were covered in less than 40 km of flight track, so are likely not statistically representative. The footprint integration can be an issue if the number of points for a given ecoregion is low so the inhomogeneity of the footprint could be the cause of the discrepancy. The high similarities between BEFs and fluxes in the remaining vast majority of subecoregions suggests that the footprint approach works well and shows that the CARB biogenic emission estimates agree generally well with observations and in many cases including well covered and highly homogenous oak woodlands (e.g. 6b) the agreement is excellent including the overall statistics (Table ~~1~~2).

Although isoprene emissions were typically very low in the Central Valley, subecoregions 7m and 7o had considerable measured emissions which were not predicted by the model. These ecoregions correspond to the San Joaquin basin and Westside Alluvial Fans and Terraces, respectively, and the landcover database is likely missing isoprene sources which were within the aircraft flux footprint but are not representative of the average for the entire subecoregion 7m or ~~7a~~7o. Another interesting observation is that the emissions, simulated by CARB for flux footprint areas follow more closely the measured emissions, than the measured BEFs from the flights compared with BEFs averaged over entire ecoregions. Overall the BEF and area emission methods are consistent in their good agreement between measurement and model.

We quantitatively compare measured and modeled fluxes in Figure ~~8~~ 7 (box plot statistics) and Figure ~~9~~ 8 (scatter plot). Unlike the BEF case which looked at BEFs averaged over entire ecoregions (of level IV) rather than for the corresponding areas of individual flux footprints, the R^2 is 0.96 with more than 70% of the points within the 95% confidence intervals. The 6h and 6ao ecoregion outliers are the most outstanding and have been discussed above. The lower emission graph shows that regions 5h, 6r, 6j, 6k, and 6z simulated emissions are overestimated. Region 5h is the Sierra Lower Mountain Forest ecoregion, and the other four are located in the northwestern coastal part of CA which is characterized by less homogenous coastal oak terrains. This ecoregion could therefore be more sensitive to accuracies in spatial footprint positioning since some but not all of these overestimates were the case in the BEF comparison. This relatively small number of overestimates is balanced by underestimates (e.g. regions 7m, 7c, 14f, 6ag) where in some cases the modeled emissions were close to zero, suggesting inaccuracies of the landcover.

Approximately 30 ecoregions showing ~~extremely~~ good agreement demonstrate the emissions are accurately simulated based on the approaches we chose in these comparisons.

On average for the entire available flux dataset, we show that the model overestimates the emissions by 19% and this is driven by a few high episodic events in the simulations which were not observed in the measured emissions. Interestingly, when comparing the median values the model is also very close to the observation with 16% underestimation by the model. This is excellent agreement which is much better than the predicted accuracy of either the modeled or measured values. The analysis points to the importance of regional assessments of the modeled emissions where in some cases discrepancies may occur.

For example, the subecoregion which was most extensively covered (~400 km, RF2, RF3, RF4) was 6b (Northern Sierran Foothills) and exhibited almost identical quantitative statistics for the model (mean 2.30, median 1.23, s.d. 2.66, min 0.008 and max 14.2 kg h-1), and measurements (mean 2.33, median 1.31, s.d. 2.67, min 0.000, and max 15.9 kg h^{-1}), and the qualitative correspondence suggests we should have high confidence in the combination of the wavelet flux measurement, footprint analysis, and the emission modeling approach. This ecoregion includes the most homogeneously distributed oak woodlands and is therefore perhaps easier to model correctly in terms of properly estimating isoprene emissions in CA.

Subecoregion 6d (Camanche Terraces) covered in 50 km of tracks was neighboring to the east with 6b and to the west with 7a, and with much sparser oaks showed lower emissions but still had reasonable agreement between the model (mean 0.364, median 0.113, s.d. 0.530, min 0.000, and max 1.70 kg h^{-1}) and measurements (mean 0.453, median 0.275, s.d. 0.440, min 0.000, and max 1.45 kg h^{-1}).

On the other hand, there are regions where quantitative agreement is less good, such as coastal 6ai (Interior Santa Lucia Range) represented in 400 km of the flight tracks where on average the model underestimated the emissions by approximately a factor of two. Another example is subecoregion 7m (San Joaquin Basin), where the model showed zero emissions (over 50 km of tracks) and isoprene emissions were measured as high as 7.58 (mean 1.73) kg h^{-1}. An opposite example in a different region (6r, East Bay Hills/Western Diablo Range) had model overestimation by about a factor of 2. This region suffered from fires with the most notable fire storm in 1991. Apart from the changes in landcover, the discrepancies may be caused by inaccuracies in meteorological driving inputs although probably to a lesser degree based on results from our sensitivity study. In a few cases at the boundary of the oaks the agreement may have been more sensitive to the full-dome flux footprint, but in majority of cases this footprint approach was sufficient to represent correctly the area sources. For highly heterogeneous areas a directional half-dome approach would work even better at finer scales. Although we focused on evaluating the model at ecoregion scale, we show the comparison (along the track) in SI Fig. 3. Despite higher uncertainty at the fine scale, the areas showing good agreement suggest that fine resolution measurements are possible and should be the focus of future campaigns, with sufficient aircraft time to allow for several repetitions of each track.

4 Conclusions

Accurate prediction of isoprene emissions is crucial for atmospheric chemistry and air quality modeling in the state of California, as well as other forested regions around the world. We used direct airborne flux measurements over the main regions in California where emissions are expected to be high to evaluate CARB's emission estimates based on their new hybrid model that is used for simulating isoprene emissions ~~of those areas and is important for development of the state implementation plan (SIP) for air quality~~ and air quality in California. The approaches that were used in the comparison of the model with observation involved comparison of airborne and landcover BEFs and independently the emissions integrated over the same footprint areas.

The overall agreement that was obtained was ~~remarkably~~ good. Mean measured and modeled emissions agreed within 50% for half of the ecoregions, while for 21% of the ecoregions the model overestimated mean measured emissions and for 29% the model underestimated emissions. On average the agreement of model with measurement was within 19% over the whole dataset. The conducted sensitivity tests for a 20% change in temperature, 20% change in PAR and 50% change in LAI altered the total mean of the simulated fluxes by up to 43%, 21%, and 40%, respectively, suggesting that these inputs are also important. Although the change in these input variables would not improve the overall agreement significantly, it could dramatically impact specific regional agreements.

The quality of the model output is directly tied to the input datasets and based on our analysis we conclude that the most important contributor to overall uncertainties in the input database is the landcover. While this was the first airborne regional evaluation of biogenic inventories for isoprene, the conclusion about the model landcover being the most important driving input is consistent with studies from other ecosystems which evaluated model landcovers (e.g. observations from Italian ecosystems (Pacheco et al., 2014) and other European ecosystems (Oderbolz et al., 2013). Future efforts should focus on developing highly resolved and highly accurate landcovers using a combination of airborne flux measurements, remote sensing data and other recently available tools such as highly sensitive time-of-flight mass spectrometry.

Acknowledgements. We gratefully acknowledge California Air Resources Board (CARB) for funding CABERNET Contract #09-339, and the CIRPAS team for help in instrument integration. We acknowledge Robin Weber and Abhinav Guha (UC Berkeley) for their contributions to the successful campaign. We would like to thank Steve Shertz (NCAR) for engineering support and Xiaoyan Jiang (NCAR) for assistance with MEGAN and WRF simulations. NCAR is sponsored by the National Science Foundation. We also acknowledge Prof. Maggi Kelly at GIF, UC Berkeley for suggestions regarding geospatial landcovers.

References

Arneth, A., Schurgers, G., Lathiere, J., Duhl, T., Beerling, D. J., Hewitt, C. N., Martin, M., and Guenther, A.: Global terrestrial isoprene emission models: sensitivity to variability in climate and vegetation, Atmospheric Chemistry and Physics, 11, 8037–8052, doi:DOI 10.5194/acp-11-8037-2011, 2011.

Ashworth, K., Wild, O., and Hewitt, C. N.: Sensitivity of isoprene emissions estimated using MEGAN to the time resolution of input climate data, Atmos. Chem. Phys., 10, 1193–1201, doi:10.5194/acp-10-1193-2010, 2010.

Benjamin, M. T., Sudol, M., Bloch, L., and Winer, A. M.: Low-emitting urban forests: a taxonomic methodology for assigning isoprene and monoterpene emission rates, Atmospheric Environment, 30, 1437–1452, 1996.

CARB: California Air Resources Board Almanac Emission Projection Data, 2015 Estimated Annual Average Emissions, published in 2013, date accessed 21 May 2016, http://www.arb.ca.gov/app/emsinv/2013/emssumcat_query.php?F_YR=2015&F_DIV=0&F_SEASON=A&SP=2013&F_AREA=CA#9, 2015.

Davis, F., Stoms, D., Hollander, A., Thomas, K., Stine, P., Odion, D., Borchert, M., Thorne, J., Gray, M., and Walker, R.: The California gap analysis project–final report, 1998.

Davis, F. W.: Mapping and monitoring terrestrial biodiversity using geographic information systems, Academia Sinica Monograph Series, 14, 461–471, 1994.

Dreyfus, G. B., Schade, G. W., and Goldstein, A. H.: Observational constraints on the contribution of isoprene oxidation to ozone production on the western slope of the Sierra Nevada, California, Journal of Geophysical Research: Atmospheres, 107, 2002.

Griffith, G., Omernik, J., and McGinley, M.: Ecoregions of the United States-Level IV (EPA), Encyclopedia of Earth. Environmental Information Coalition, National Council for Science and the Environment, Washington, DC, 2008.

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, Journal of Geophysical Research: Atmospheres, 100, 8873–8892, doi:10.1029/94JD02950, 1995.

Guenther, A., Karl, T., Harley, P., Wiedinmyer, C., Palmer, P. I., and Geron, C.: Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature), Atmos. Chem. Phys., 6, 3181–3210, doi:10.5194/acp-6-3181-2006, 2006.

Guenther, A. B., Zimmerman, P. R., Harley, P. C., Monson, R. K., and Fall, R.: Isoprene and monoterpene emission rate variability: Model evaluations and sensitivity analyses, Journal of Geophysical Research: Atmospheres, 98, 12 609–12 617, doi:10.1029/93JD00527, http://dx.doi.org/10.1029/93JD00527, 1993.

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, Geoscientific Model Development, 5, 1471–1492, doi:10.5194/gmd-5-1471-2012, 2012.

Harley, P., Fridd-Stroud, V., Greenberg, J., Guenther, A., and Vasconcellos, P.: Emission of 2-methyl-3-buten-2-ol by pines: A potentially large natural source of reactive carbon to the atmosphere, Journal of Geophysical Research: Atmospheres, 103, 25 479–25 486, doi:10.1029/98JD00820, 1998.

Henze, D. K. and Seinfeld, J. H.: Global secondary organic aerosol from isoprene oxidation, Geophysical Research Letters, 33, 2006.

Homer, C., Huang, C. Q., Yang, L. M., Wylie, B., and Coan, M.: Development of a 2001 National Land-Cover Database for the United States, Photogrammetric Engineering and Remote Sensing, 70, 829–840, 2004.

Karl, T., Misztal, P. K., Jonsson, H. H., Shertz, S., Goldstein, A. H., and Guenther, A. B.: Airborne Flux Measurements of BVOCs above Californian Oak Forests: Experimental Investigation of Surface and Entrainment Fluxes, OH Densities, and Damkohler Numbers, Journal of the Atmospheric Sciences, 70, 3277–3287, doi:Doi 10.1175/Jas-D-13-054.1, <GotoISI>://000325147900017, 2013.

Karlik, J. F., Chung, Y. J., and Winer, A. M.: Biogenic emission inventory development: field assessment of the GAP vegetation database in California, Physics and Chemistry of the Earth, Parts A/B/C, 28, 315–325, 2003.

Kleinman, L., Kuang, C., Sedlacek, A., Senum, G., Springston, S., Wang, J., Zhang, Q., Jayne, J., Fast, J., Hubbe, J., et al.: What do correlations tell us about anthropogenic–biogenic interactions and SOA formation in the Sacramento Plume during CARES?, Atmospheric Chemistry and Physics Discussions, 15, 25 381–25 431, 2015.

Marais, E. A., Jacob, D. J., Guenther, A., Chance, K., Kurosu, T. P., Murphy, J. G., Reeves, C. E., and Pye, H. O. T.: Improved model of isoprene emissions in Africa using Ozone Monitoring Instrument (OMI) satellite observations of formaldehyde: implications for oxidants and particulate matter, Atmos. Chem. Phys., 14, 7693–7703, doi:10.5194/acp-14-7693-2014, 2014.

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, Atmospheric Chemistry and Physics, 11, 8995–9017, doi:DOI 10.5194/acp-11-8995-2011, 2011.

Misztal, P. K., Karl, T., Weber, R., Jonsson, H. H., Guenther, A. B., and Goldstein, A. H.: Airborne flux measurements of biogenic isoprene over California, Atmospheric Chemistry and Physics, 14, 10 631–10 647, doi:DOI 10.5194/acp-14-10631-2014, 2014.

Müller, J. F., Stavrakou, T., Wallens, S., De Smedt, I., Van Roozendael, M., Potosnak, M. J., Rinne, J., Munger, B., Goldstein, A., and Guenther, A. B.: Global isoprene emissions estimated using MEGAN, ECMWF analyses and a detailed canopy environment model, Atmos. Chem. Phys., 8, 1329–1341, doi:10.5194/acp-8-1329-2008, aCP, 2008.

Nowak, D. J., Civerolo, K. L., Rao, S. T., Sistla, G., Luley, C. J., and Crane, D. E.: A modeling study of the impact of urban trees on ozone, Atmospheric environment, 34, 1601–1613, 2000.

Oderbolz, D., Aksoyoglu, S., Keller, J., Barmpadimos, I., Steinbrecher, R., Skjøth, C. A., Plaß-Dülmer, C., and Prévôt, A.: A comprehensive emission inventory of biogenic volatile organic compounds in Europe: improved seasonality and land-cover, Atmospheric Chemistry and Physics, 13, 1689–1712, 2013.

Pacheco, C. K., Fares, S., and Ciccioli, P.: A highly spatially resolved GIS-based model to assess the isoprenoid emissions from key Italian ecosystems, Atmospheric Environment, 96, 50–60, 2014.

Potosnak, M. J., LeStourgeon, L., Pallardy, S. G., Hosman, K. P., Gu, L., Karl, T., Geron, C., and Guenther, A. B.: Observed and modeled ecosystem isoprene fluxes from an oak-dominated temperate forest and the influence of drought stress, Atmospheric Environment, 84, 314–322, 2014.

Pugh, T., Ashworth, K., Wild, O., and Hewitt, C.: Effects of the spatial resolution of climate data on estimates of biogenic isoprene emissions, Atmospheric Environment, 70, 1–6, 2013.

Rollins, A., Browne, E., Min, K.-E., Pusede, S., Wooldridge, P., Gentner, D., Goldstein, A., Liu, S., Day, D., Russell, L., et al.: Evidence for NOx control over nighttime SOA formation, Science, 337, 1210–1212, 2012.

Rosenstiel, T. N., Potosnak, M. J., Griffin, K. L., Fall, R., and Monson, R. K.: Increased CO2 uncouples growth from isoprene emission in an agriforest ecosystem, Nature, 421, 256–259, 2003.

Scott, J. M., Davis, F., Csuti, B., Noss, R., Butterfield, B., Groves, C., Anderson, H., Caicco, S., D'Erchia, F., Edwards Jr, T. C., et al.: Gap analysis: a geographic approach to protection of biological diversity, Wildlife monographs, pp. 3–41, 1993.

Scott, K. I. and Benjamin, M. T.: Development of a biogenic volatile organic compounds emission inventory for the SCOS97-NARSTO domain, Atmospheric Environment, 37, S39–S49, doi:Doi 10.1016/S1352-2310(03)00381-9, 2003.

Sindelarova, K., Granier, C., Bouarar, I., Guenther, A., Tilmes, S., Stavrakou, T., Müller, J. F., Kuhn, U., Stefani, P., and Knorr, W.: Global data set of biogenic VOC emissions calculated by the MEGAN model over the last 30 years, Atmos. Chem. Phys., 14, 9317–9341, doi:10.5194/acp-14-9317-2014, http://www.atmos-chem-phys.net/14/9317/2014/, aCP, 2014.

Situ, S., Wang, X., Guenther, A., Zhang, Y., Wang, X., Huang, M., Fan, Q., and Xiong, Z.: Uncertainties of isoprene emissions in the MEGAN model estimated for a coniferous and broad-leaved mixed forest in Southern China, Atmospheric Environment, 98, 105–110, 2014.

Skamarock, W., Klemp, J., Dudhia, J., Gill, D., and Barker, D.: Coauthors, 2008: A Description of the Advanced Research WRF Version 3. NCAR Technical Note, Report, NCAR/TN–475+ STR, 2005.

Steiner, A. L., Cohen, R., Harley, R., Tonse, S., Millet, D., Schade, G., and Goldstein, A.: VOC reactivity in central California: comparing an air quality model to ground-based measurements, Atmospheric Chemistry and Physics, 8, 351–368, 2008.

Unger, N., Harper, K., Zheng, Y., Kiang, N. Y., Aleinov, I., Arneth, A., Schurgers, G., Amelynck, C., Goldstein, A., Guenther, A., Heinesch, B., Hewitt, C. N., Karl, T., Laffineur, Q., Langford, B., A. McKinney, K., Misztal, P., Potosnak, M., Rinne, J., Pressley, S., Schoon, N., and Serça, D.: Photosynthesis-dependent isoprene emission from leaf to planet in a global carbon-chemistry-climate model, Atmos. Chem. Phys., 13, 10 243–10 269, doi:10.5194/acp-13-10243-2013, 2013.

USEPA: USEPA, Level III and IV Ecoregions of the Continental United States, http://www.epa.gov/wed/pages/ecoregions/level_iii_iv.htm, 2014.

Vaughan, A. R., Lee, J. D., Misztal, P. K., Metzger, S., Shaw, M. D., Lewis, A. C., Purvis, R. M., Carslaw, D. C., Goldstein, A. H., Hewitt, C. N., Davison, B., Beevers, S. D., and Karl, T. G.: Spatially resolved flux measurements of NOx from London suggest significantly higher emissions than predicted by inventories, Faraday Discuss., pp. –, doi:10.1039/C5FD00170F, http://dx.doi.org/10.1039/C5FD00170F, 2016.

Weil, J. C. and Horst, T. W.: Footprint Estimates for Atmospheric Flux Measurements in the Convective Boundary-Layer, Precipitation Scavenging and Atmosphere-Surface Exchange, Vols 1-3, pp. 717–728, 1992.

Winer, A. M., Arey, J., Atkinson, R., Aschmann, S. M., Long, W. D., Morrison, C. L., and Olszyk, D. M.: Emission Rates of Organics from Vegetation in California Central Valley, Atmospheric Environment Part a-General Topics, 26, 2647–2659, doi:Doi 10.1016/0960-1686(92)90116-3, 1992.

Wolfe, G. M., Hanisco, T. F., Arkinson, H. L., Bui, T. P., Crounse, J. D., Dean-Day, J., Goldstein, A., Guenther, A., Hall, S. R., Huey, G., Jacob, D. J., Karl, T., Kim, P. S., Liu, X., Marvin, M. R., Mikoviny, T., Misztal, P. K., Nguyen, T. B., Peischl, J., Pollack, I., Ryerson, T., St. Clair, J. M., Teng, A., Travis, K. R., Ullmann, K., Wennberg, P. O., and Wisthaler, A.: Quantifying sources and sinks of reactive gases in the lower atmosphere using airborne flux observations, Geophysical Research Letters, 42, doi:10.1002/2015gl065839, 2015.

Worton, D. R., Surratt, J. D., LaFranchi, B. W., Chan, A. W., Zhao, Y., Weber, R. J., Park, J.-H., Gilman, J. B., De Gouw, J., Park, C., et al.: Observational insights into aerosol formation from isoprene, Environmental science & technology, 47, 11 403–11 413, 2013.

Yuan, B., Kaser, L., Karl, T., Graus, M., Peischl, J., Campos, T. L., Shertz, S., Apel, E. C., Hornbrook, R. S., Hills, A., Gilman, J. B., Lerner, B. M., Warneke, C., Flocke, F. M., Ryerson, T. B., Guenther, A. B., and de Gouw, J. A.: Airborne flux measurements of methane and volatile organic compounds over the Haynesville and Marcellus shale gas production regions, Journal of Geophysical Research: Atmospheres, 120, 6271–6289, doi:10.1002/2015jd023242, 2015.

Table 1. Characteristics of each model in the regional application for CA.

Model	Inputs	EF Landcover	Resolution	History of T and PAR	CEM^a
MEGAN 2.04	T, PAR, LAI (monthly of 2003), explicit EFs (no canopy type used), wilting point and soil moisture (not used), leaf age (not used)	Landcover 2.1	1 x 1 km	no	yes
MEGAN 2.1	T, PAR, LAI (8 day MODIS 2003-2011), explicit EFs (no canopy type used), wilting point and soil moisture (not used), leaf age (not used), CO2 (not used)	Landcover 2.2	1 x 1 km	yes	yes
BEIGIS	T, PAR, LAI (8 day MODIS)+phenology, explicit EFs	GAP BEIGIS	4 x 4 km	no	no
CARB HYBRID	T, PAR, LAI (8 day MODIS 2011), explicit EFs	Landcover 2.2	2 x 2 km (some inputs 4 x 4 km)	yes	no

^{a} Canopy Environment Model

Table 2. Summary quantitative statistics for CABERNET and CARB model's emissions (kg h^{-1})*

			CABERNET			CARB MODEL		
Ecoregion	Description	*N*	Mean	Median	SD	Mean	Median	SD
Total	All ecoregions	1746	1.38	0.416	2.74	1.64	0.360	4.34
Good agreement								
5e	Northern Sierra Lower Montane Forests	29	1.21	0.992	1.22	0.852	0.622	0.842
5h	Central Sierra Lower Montane Forests	26	1.48	1.11	1.509	2.27	1.96	1.70
6aa	Eastern Hills	28	0.113	0.000	0.231	0.095	0.026	0.216
6al	Salinas-Cholame Hills	44	0.562	0.381	0.730	0.460	0.215	0.848
6ap	Solomon-Purisima-Santa Ynez Hills	31	1.16	0.749	1.15	1.08	0.720	1.18
6b	Northern Sierran Foothills	196	2.33	1.31	2.67	2.30	1.23	2.66
6c	Southern Sierran Foothills	181	1.24	0.647	1.65	0.851	0.383	1.13
6d	Camanche Terraces	24	0.453	0.275	0.440	0.364	0.113	0.530
6l	Napa-Sonoma-Russian River Valleys	22	0.505	0.346	0.569	0.770	0.326	1.26
6z	Diablo Range	136	0.944	0.252	1.88	1.70	0.592	2.66
7a	Northern Terraces	27	0.266	0.130	0.365	0.182	0.074	0.262
Model underestimates								
6ac	Temblor Range/Elk Hills	36	0.073	0.037	0.093	0.000	0.00	0.00
6af	Salinas Valley	24	0.223	0.00	0.341	0.140	0.040	0.214
6ag	Northern Santa Lucia Range	30	4.09	1.05	5.47	1.22	0.607	1.39
6ai	Interior Santa Lucia Range	201	2.83	1.17	4.41	1.24	0.307	2.92
6ak	Paso Robles Hills and Valleys	36	0.927	0.513	1.24	0.453	0.108	0.975
6g	North Coast Range Eastern Slopes	20	1.10	0.297	1.68	0.582	0.247	0.918
7j	Delta	35	0.358	0.295	0.337	0.015	0.000	0.050
7m	San Joaquin Basin	23	1.73	0.234	2.65	0.000	0.000	0.000
7o	Westside Alluvial Fans and Terraces	38	0.683	0.203	0.994	0.004	0.000	0.014
7p	Gigantic Alluvial Fans and Terraces	22	0.053	0.026	0.129	0.000	0.000	0.000
7t	South Valley Alluvium	23	0.025	0.005	0.066	0.000	0.000	0.000
Model overestimates								
6aj	Southern Santa Lucia Range	23	0.665	0.205	0.820	4.72	2.59	4.84
6j	Mayacmas Mountains	41	0.272	0.148	0.382	2.11	0.884	5.46
6k	Napa-Sonoma-Lake Volcanic Highlands	22	1.241	0.423	1.80	6.86	1.92	12.7
6r	East Bay Hills/ Western Diablo Range	204	1.516	0.388	3.06	3.87	0.854	6.80
78q	Outer North Coast Ranges	32	1.040	0.297	1.64	4.67	1.32	10.8

*Ecoregions with N<20 (<40 km) were omitted from this table

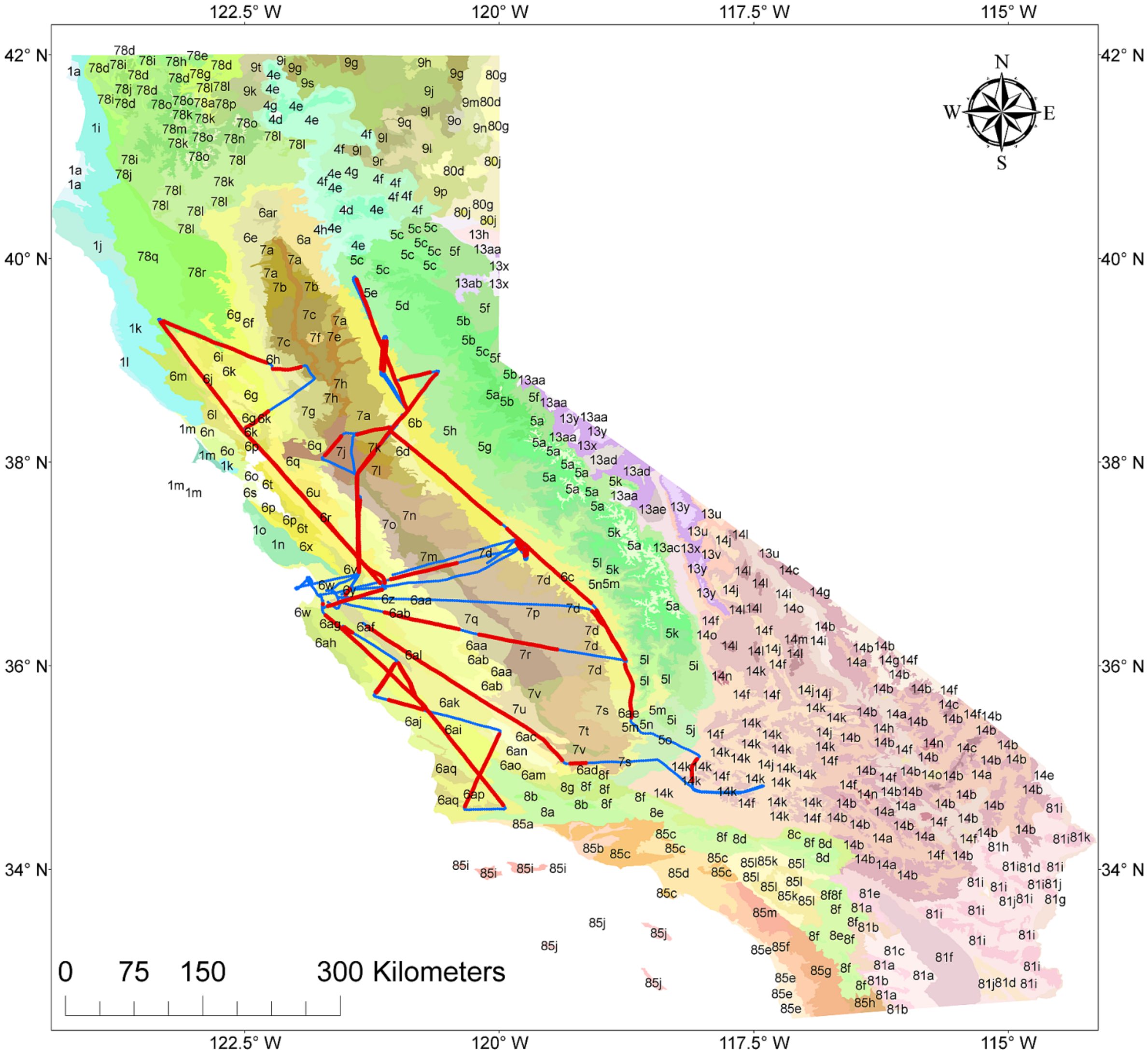


Figure 1. USEPA Ecoregion map with overlaid CABERNET flight tracks covering most of code 6 ecoregions. The legend with code descriptions is provided in Supplementary Fig. 1. The shapefiles used to produce the map in ArcGIS were downloaded from ftp://ftp.epa.gov/wed/ecoregions/ca/.

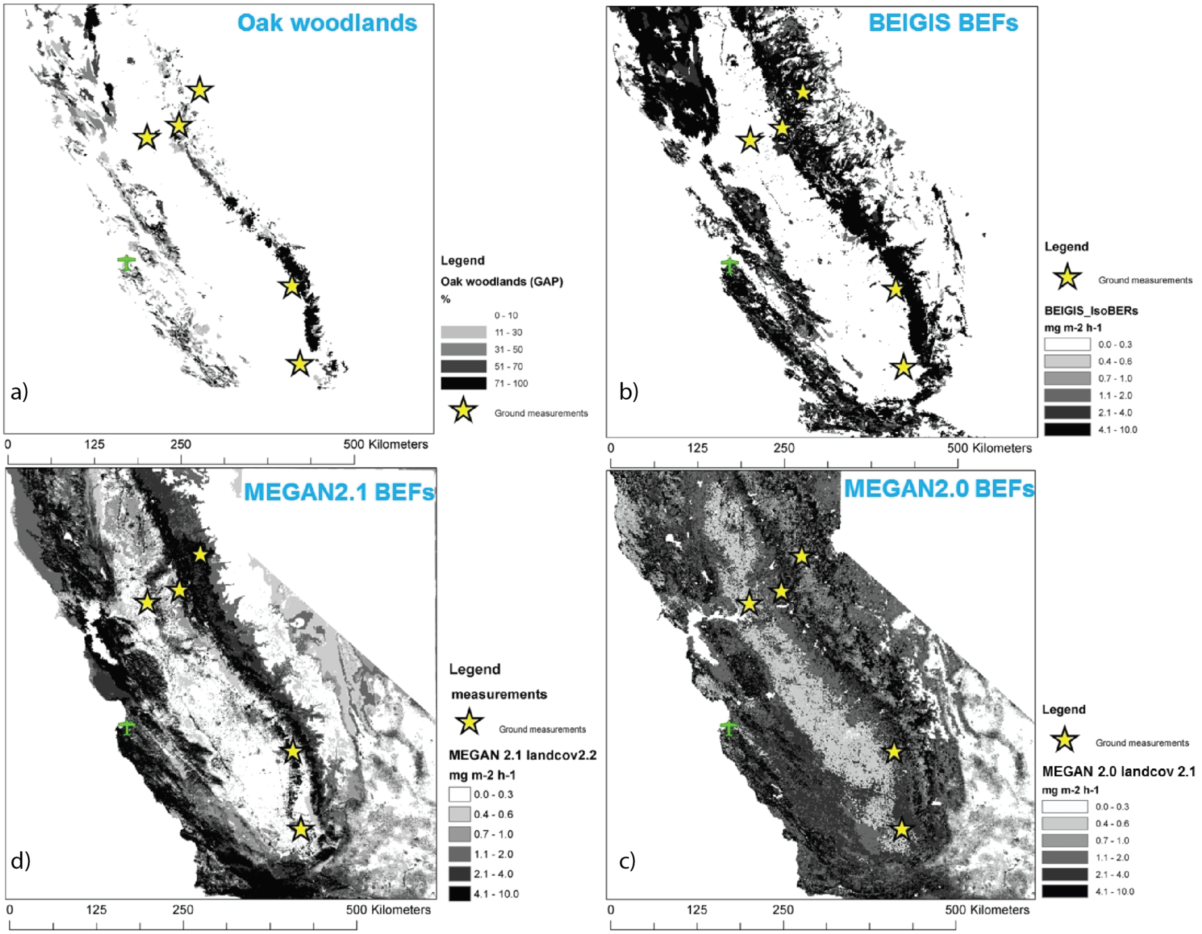


Figure 2. Landcovers used by the models. a) GAP's oak woodlands, b) BEIGIS emission factors ~~(~~as dtiso+eiso (the sum of emission factors for deciduous and evergreen trees) derived from the GAP database, c) MEGAN v.2.04 isoprene emission factors derived from landcover v.2.1, and d) MEGAN v.2.1 isoprene emission factors obtained from the most recent landcover v.2.2.

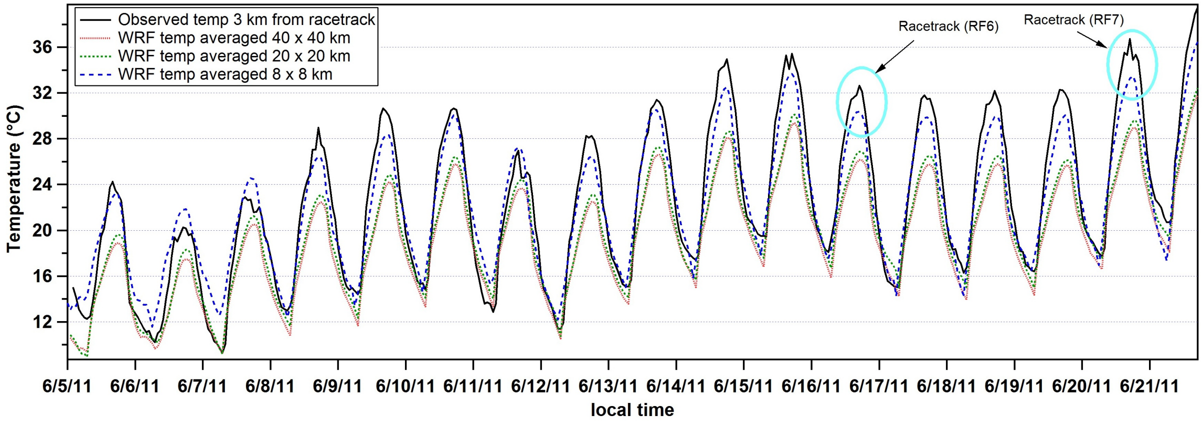


Figure 3. Resolution effect in WRF on temperature bias. The discrepancy between the temperature observed near racetrack and WRF decreased as a function of resolution. At 8 x 8 km the bias was very small on most days, but occasionally up to 2 °C was observed.

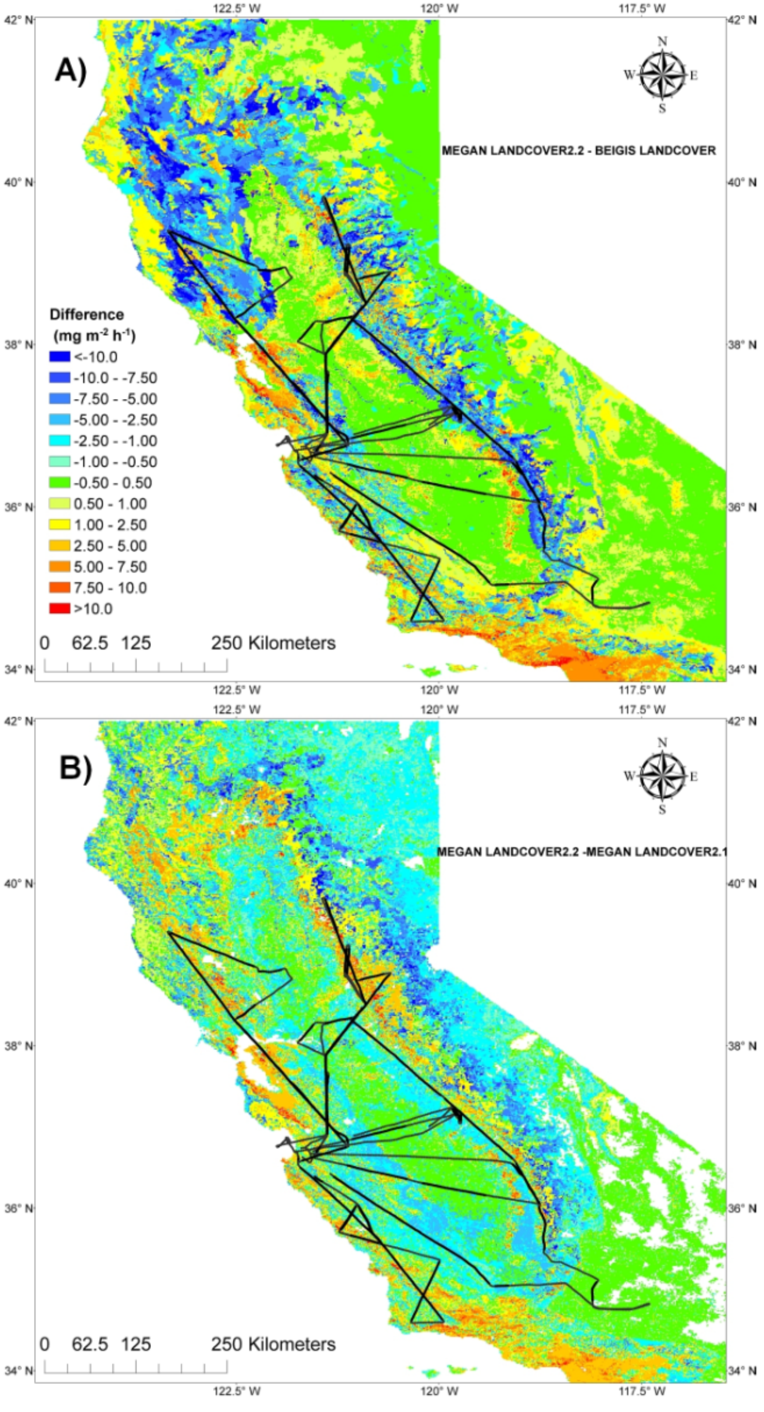


Figure 4. Absolute BEF differences of a) MEGAN v.2.1 Landcover v.2.2 and BEIGIS GAP Landcover and b) MEGAN v.2.1 Landcover v.2.2 and MEGAN v.2.04 Landcover v.2.1.

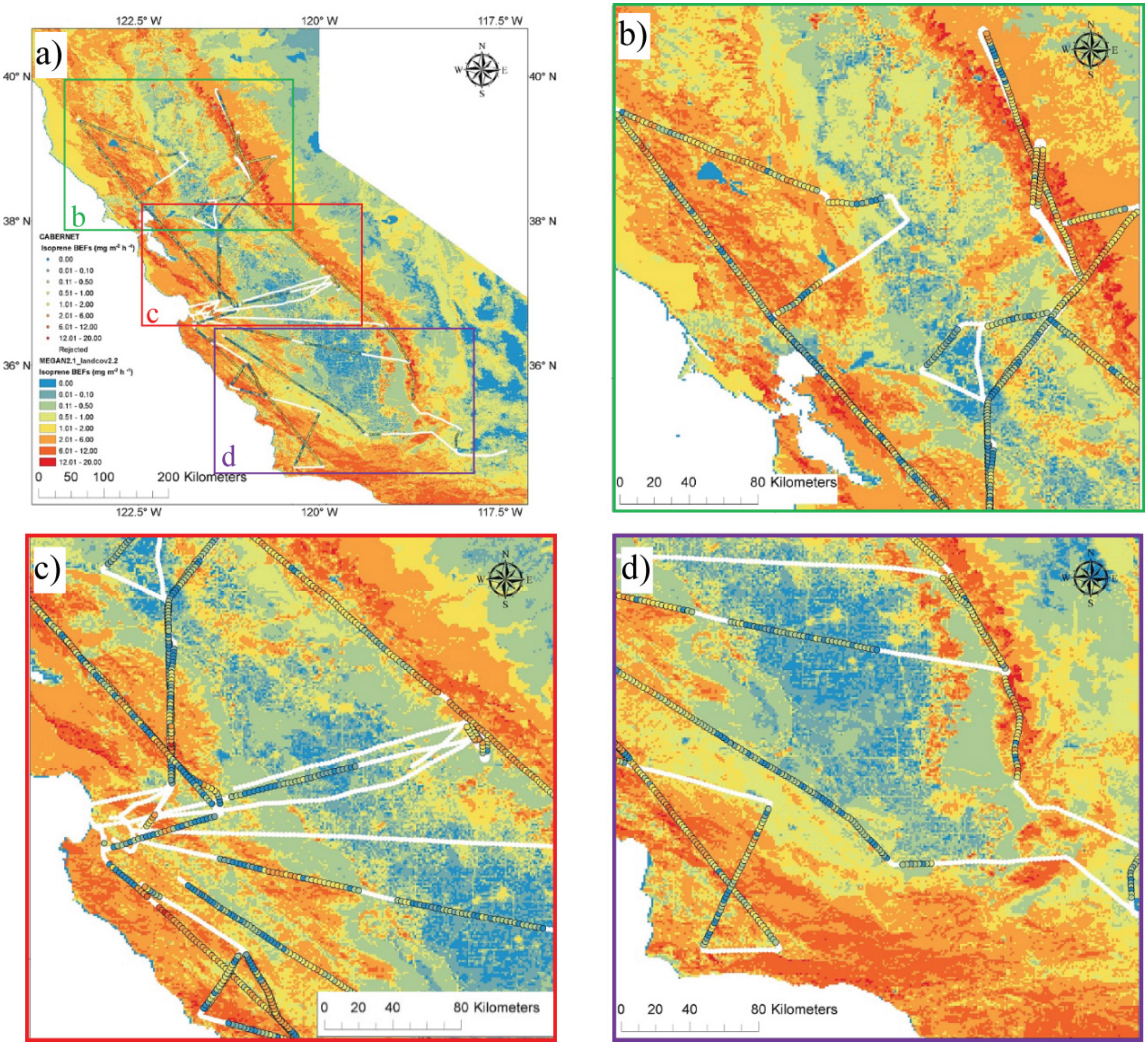


Figure 5. a) Comparison of airborne BEFs with MEGAN's landcover 2.2 for isoprene (airborne BEFs are subject to additional uncertainties introduced from T, and PAR used in normalization). Magnified areas are shown for b) northwest (including Northern Coastal Ranges to the left and Northern Sierra Foothills to the right, the middle area relates to the Central Valley and the San Joaquin Delta), c) central, and d) southeast tracks.

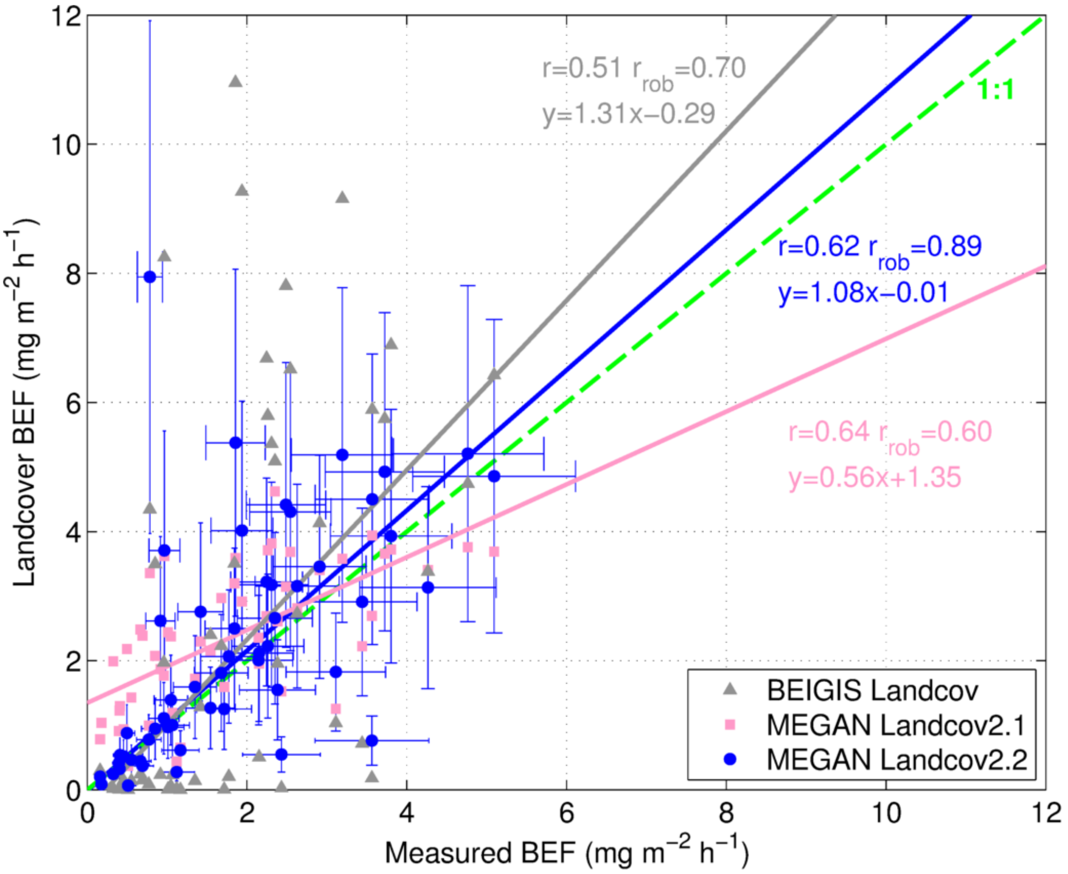


Figure 6. Comparison of measured versus modeled (MEGAN Landcover2.2, MEGAN Landcover 2.1, and BEIGIS) Basal Emission Factors averaged by USEPA ecoregion. Note: the number of averaged points in each ecoregion may be different and not necessarily representative of the entire ecoregion.

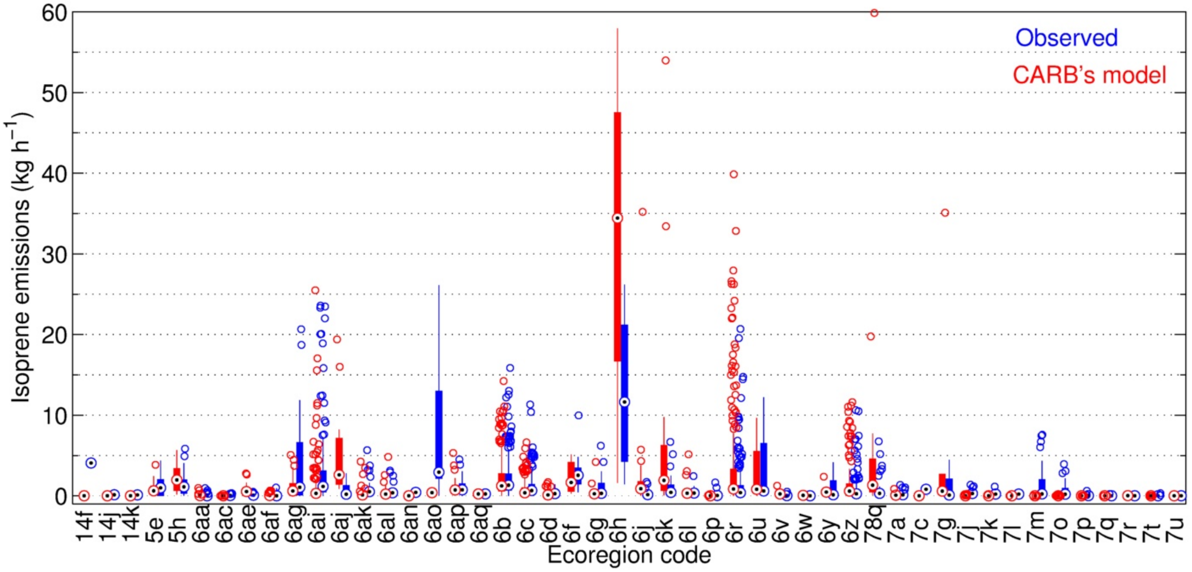
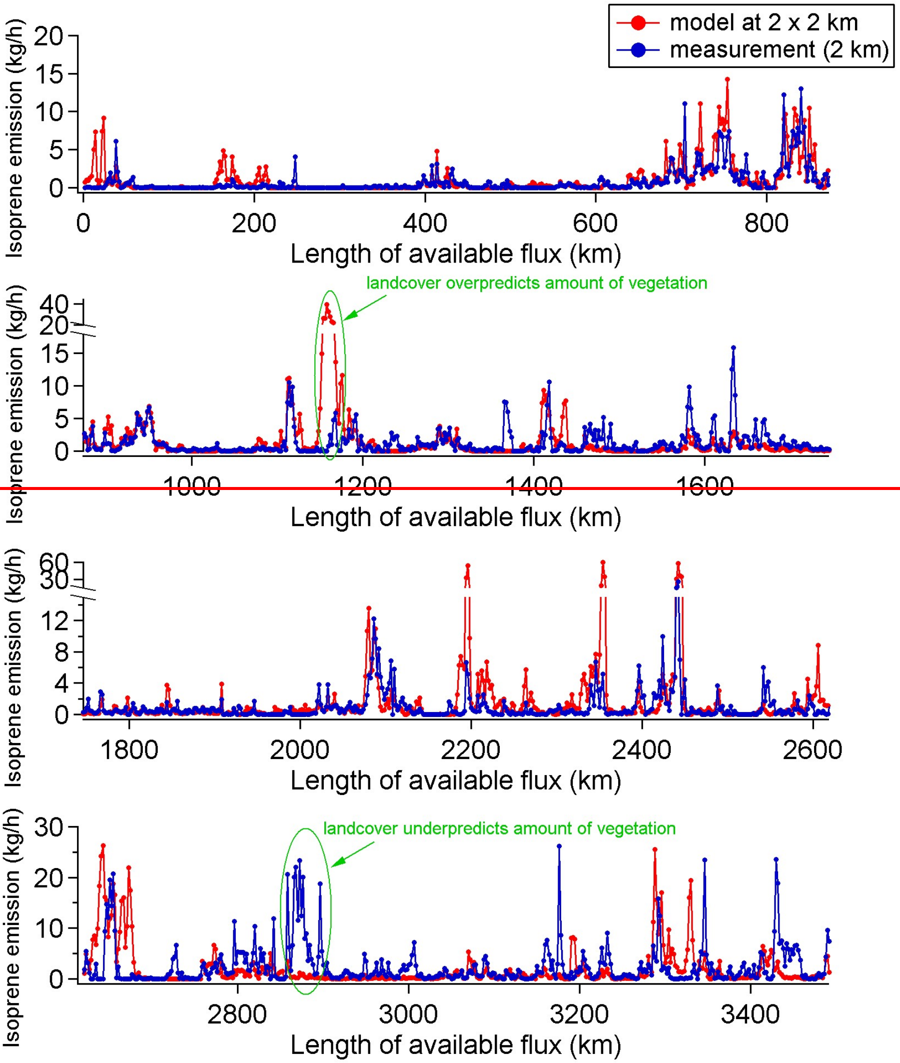


Figure 7. Box plots showing distribution of emissions in each of the level IV ecoregions. The boxes correspond to midrange (25th to 75th percentiles), the whiskers indicate variability outside the lower and upper quartiles, and the circles denote outlying emission hotspots.



~~**Figure 7** Time series for modeled and measured isoprene fluxes using the approximated circular footprint areas (only the data when flux was available are shown) along the full length of the flight tracks during the CABERNET campaign.~~

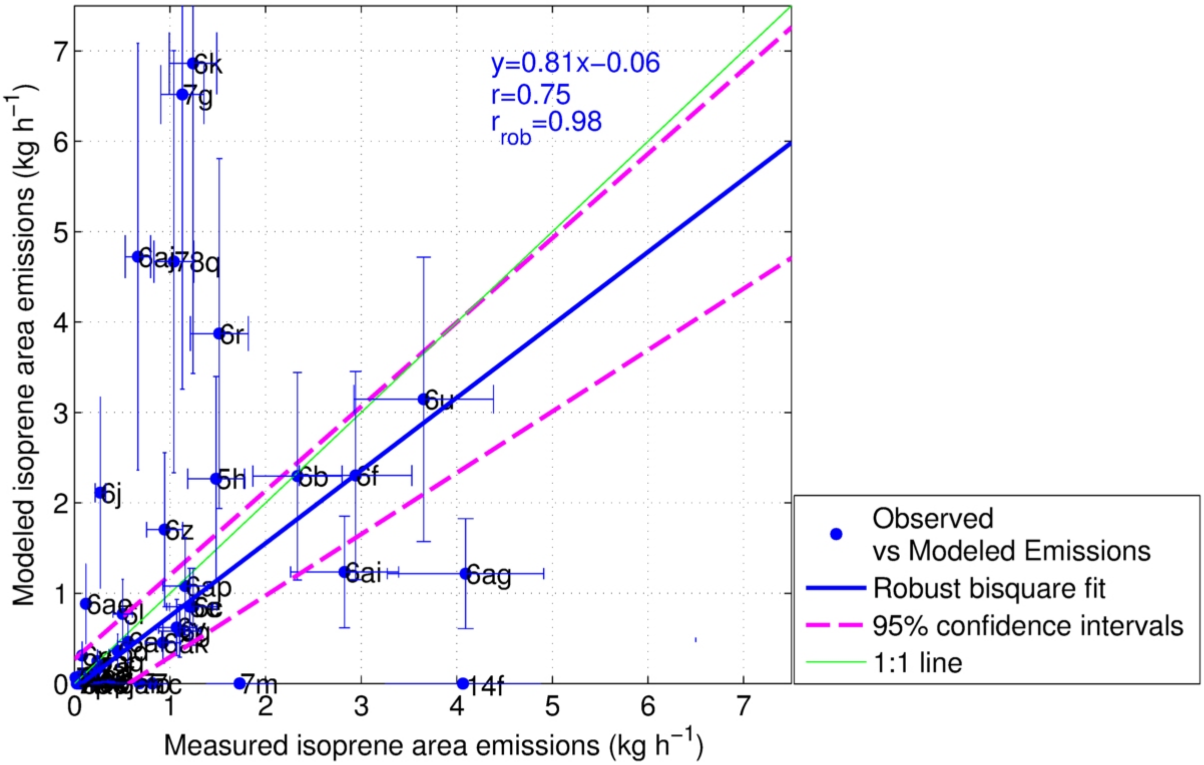


Figure 8. Scatter plot for the ecoregion averaged area emissions. The model dataset used is the hybrid CARB model. The vertical error bars represent the 50% model uncertainty and the horizontal error bars represent the 20% uncertainty of the measurement (applicable to ecoregions covered in more than 40 km – see Table ~~1~~2).

Supplementary information for Misztal et al. “Evaluation of regional isoprene emission factors and modeled fluxes in California”

S1. Ecoregion codes (Legend to Figure 1)

Legend

- Isop flux available
- Isop flux anavailable

ca_eco_l4

CA_Ecoregion_level4

L4_KEY

13aa	Sierra Nevada-Influenced Semiarid Hills and Basins
13ab	Sierra Valley
13ac	Upper Owens Valley
13ad	Mono-Adobe Valleys
13ae	Bishop Volcanic Tableland
13h	Lahontan and Tonopah Playas
13u	Tonopah Basin
13v	Tonopah Sagebrush Foothills
13x	Sierra Nevada-Influenced Ranges
13y	Sierra Nevada-Influenced High Elevation Mountains
14a	Eastern Mojave Basins
14b	Eastern Mojave Low Ranges and Arid Footslopes
14c	Eastern Mojave Mountain Woodland and Shrubland
14e	Arid Valleys and Canyonlands
14f	Mojave Playas
14g	Amargosa Desert
14h	Death Valley/Mojave Central Trough
14i	Mesquite Flat/Badwater Basin
14j	Western Mojave Basins
14k	Western Mojave Low Ranges and Arid Footslopes
14l	Western Mojave Mountain Woodland and Shrubland
14m	Western Mojave High Elevation Mountains
14n	Mojave Lava Fields
14o	Mojave Sand Dunes
1a	Coastal Lowlands
1i	Northern Franciscan Redwood Forest
1j	King Range/Mattole Basin
1k	Coastal Franciscan Redwood Forest
1l	Fort Bragg/Fort Ross Terraces
1m	Point Reyes/Farallon Islands
1n	Santa Cruz Mountains
1o	San Mateo Coastal Hills
4d	Cascade Subalpine/Alpine
4e	High Southern Cascades Montane Forest
4f	Low Southern Cascades Mixed Conifer Forest
4g	California Cascades Eastside Conifer Forest
4h	Southern Cascades Foothills
5a	Sierran Alpine
5b	Northern Sierra Subalpine Forests
5c	Northern Sierra Upper Montane Forests
5d	Northern Sierra Mid-Montane Forests
5e	Northern Sierra Lower Montane Forests
5f	Northeastern Sierra Mixed Conifer-Pine Forests
5g	Central Sierra Mid-Montane Forests
5h	Central Sierra Lower Montane Forests
5i	Eastern Sierra Great Basin Slopes
5j	Eastern Sierra Mojavean Slopes
5k	Southern Sierra Subalpine Forests
5l	Southern Sierra Upper Montane Forests
5m	Southern Sierra Mid-Montane Forests
5n	Southern Sierra Lower Montane Forest and Woodland
5o	Tehachapi Mountains
6a	Tuscan Flows
6aa	Eastern Hills
6ab	Pleasant Valley/Kettleman Plain
6ac	Temblor Range/Elk Hills
6ad	Grapevine Transition
6ae	Tehachapi Foothills
6af	Salinas Valley
6ag	Northern Santa Lucia Range
6ah	Santa Lucia Coastal Forest and Woodland
6ai	Interior Santa Lucia Range
6aj	Southern Santa Lucia Range
6ak	Paso Robles Hills and Valleys
6al	Salinas-Cholame Hills
6am	Cuyama Valley
6an	Carrizo Plain
6ao	Caliente Range
6ap	Solomon-Purisima-Santa Ynez Hills
6aq	Santa Maria/Santa Ynez Valleys
6ar	Upper Sacramento River Alluvium
6b	Northern Sierran Foothills
6c	Southern Sierran Foothills
6d	Camanche Terraces
6e	Tehama Terraces
6f	Foothill Ridges and Valleys
6g	North Coast Range Eastern Slopes
6h	Western Valley Foothills/Dunnigan Hills
6i	Clear Lake Hills and Valleys
6j	Mayacmas Mountains
6k	Napa-Sonoma-Lake Volcanic Highlands
6l	Napa-Sonoma-Russian River Valleys
6m	Sonoma-Mendocino Mixed Forest
6n	Bodega Coastal Hills
6o	Marin Hills
6p	Bay Flats
6q	Suisun Terraces and Low Hills
6r	East Bay Hills/Western Diablo Range
6s	San Francisco Peninsula
6t	Bay Terraces/Lower Santa Clara Valley
6u	Livermore Hills and Valleys
6v	Upper Santa Clara Valley
6w	Monterey Bay Plains and Terraces
6x	Leeward Hills/Western Diablo Range
6y	Gabilan Range
6z	Diablo Range
78a	Rogue/Illinois/Scott Valleys
78d	Serpentine Siskiyous
78e	Inland Siskiyous
78g	Klamath River Ridges
78h	Border High-Siskiyous
78i	Western Klamath Low Elevation Forests
78j	Western Klamath Montane Forests
78k	Eastern Klamath Low Elevation Forests
78l	Eastern Klamath Montane Forests
78m	Marble/Salmon Mountains-Trinity Alps
78n	Scott Mountains
78o	Klamath Subalpine
78p	Duzel Rock
78q	Outer North Coast Ranges
78r	High North Coast Ranges
7a	Northern Terraces
7b	North Valley Alluvium
7c	Butte Sink/Sutter and Colusa Basins
7d	Southern Hardpan Terraces
7e	Sacramento/Feather Riverine Alluvium
7f	Sutter Buttes
7g	Yolo Alluvial Fans
7h	Yolo/American Basin
7j	Delta
7k	Lodi Alluvium
7l	Stockton Basin
7m	San Joaquin Basin
7n	Manteca/Merced Alluvium
7o	Westside Alluvial Fans and Terraces
7p	Granitic Alluvial Fans and Terraces
7q	Panoche and Cantua Fans and Basins
7r	Tulare Basin/Fresno Slough
7s	Kern Terraces
7t	South Valley Alluvium
7u	Antelope Plain
7v	Southern Clayey Basins
80d	Pluvial Lake Basins
80g	High Lava Plains
80j	Semiarid Uplands
81a	Western Sonoran Mountains
81b	Western Sonoran Mountain Woodland and Shrubland
81c	Western Sonoran Basins
81d	Sand Hills/Sand Dunes
81e	Upper Coachella Valley and Hills
81f	Imperial/Lower Coachella Valleys
81g	Lower Colorado/Gila River Valleys
81h	Sonoran Playas
81i	Central Sonoran/Colorado Desert Mountains
81j	Central Sonoran/Colorado Desert Basins
81k	Arizona Upland/Eastern Sonoran Mountains
85a	Santa Barbara Coastal Plain and Terraces
85b	Oxnard Plain and Valleys
85c	Venturan-Angeleno Coastal Hills
85d	Los Angeles Plain
85e	Diegan Coastal Terraces
85f	Diegan Coastal Hills and Valleys
85g	Diegan Western Granitic Foothills
85h	Morena/Boundary Mountain Chaparral
85i	Northern Channel Islands
85j	Southern Channel Islands
85k	Inland Valleys
85l	Inland Hills
85m	Santa Ana Mountains
8a	Western Transverse Range Lower Montane Shrub and Woodland
8b	Western Transverse Range Montane Forest
8c	Arid Montane Slopes
8d	Southern California Subalpine/Alpine
8e	Southern California Lower Montane Shrub and Woodland
8f	Southern California Montane Conifer Forest
8g	Northern Transverse Range
9g	Klamath/Goose Lake Basins
9h	Fremont Pine/Fir Forest
9i	Southern Cascades Slope
9j	Klamath Juniper Woodland/Devils Garden
9k	Shasta Valley
9l	Pit River Valleys
9m	Warner Mountains
9n	High Elevation Warner Mountains
9o	Likely Tableland
9p	Modoc/Lassen Juniper-Shrub Hills and Mountains
9q	Adin/Horsehead Mountains Forest and Woodland
9r	Adin/Dixie Low Hills
9s	Modoc Lava Flows and Buttes
9t	Old Cascades

Figure S1. Legend to Figure 1 describing ecoregion codes.

S2. MEGAN architecture and main differences between versions

The main differences of MEGAN v.2.1 to MEGAN v.2.04 are:

1) v2.04 does not have soil moisture or CO2 response (but these were not used for MEGAN v.2.1 simulations in this study);

2) MEGAN v.2.04 uses a different emission factor database and has different light response algorithms (which are nearly the same for isoprene and mostly impact other compounds);

3) MEGAN v.2.04 uses different parameters in the canopy environment model.

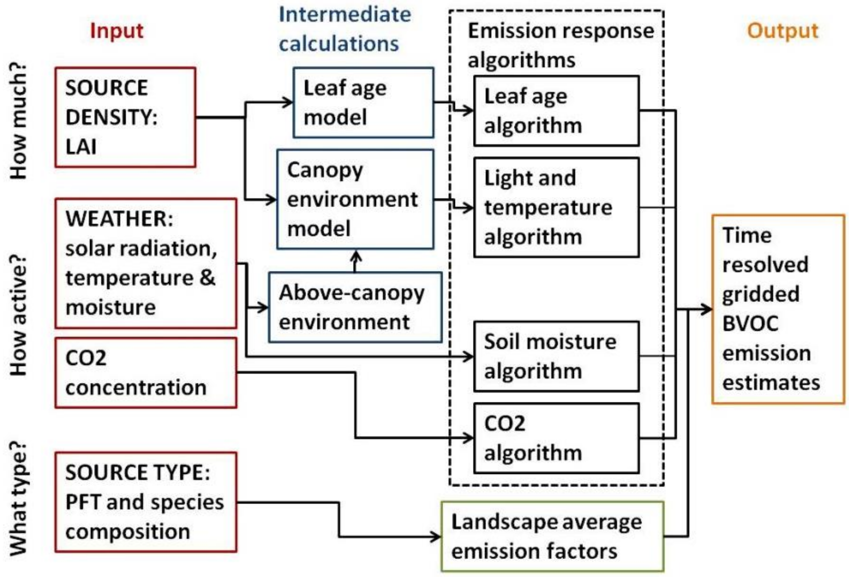


Figure S2. Schematic of MEGAN v.2.1 model components and driving variables (taken from Guenther et al., 2012).

S3. Timeseries of simulated and observed emissions

In Figure S3, the time series of simulated and measured emissions are shown (plotted along the complete flight tracks).

Local similarities and discrepancies are observed in specific areas along the flight track and are discussed in the manuscript. Although there are different sources of uncertainty, the largest discrepancy occurs if the trees are significantly under or overrepresented, which could be due to fires, new growth, or incomplete landcover.

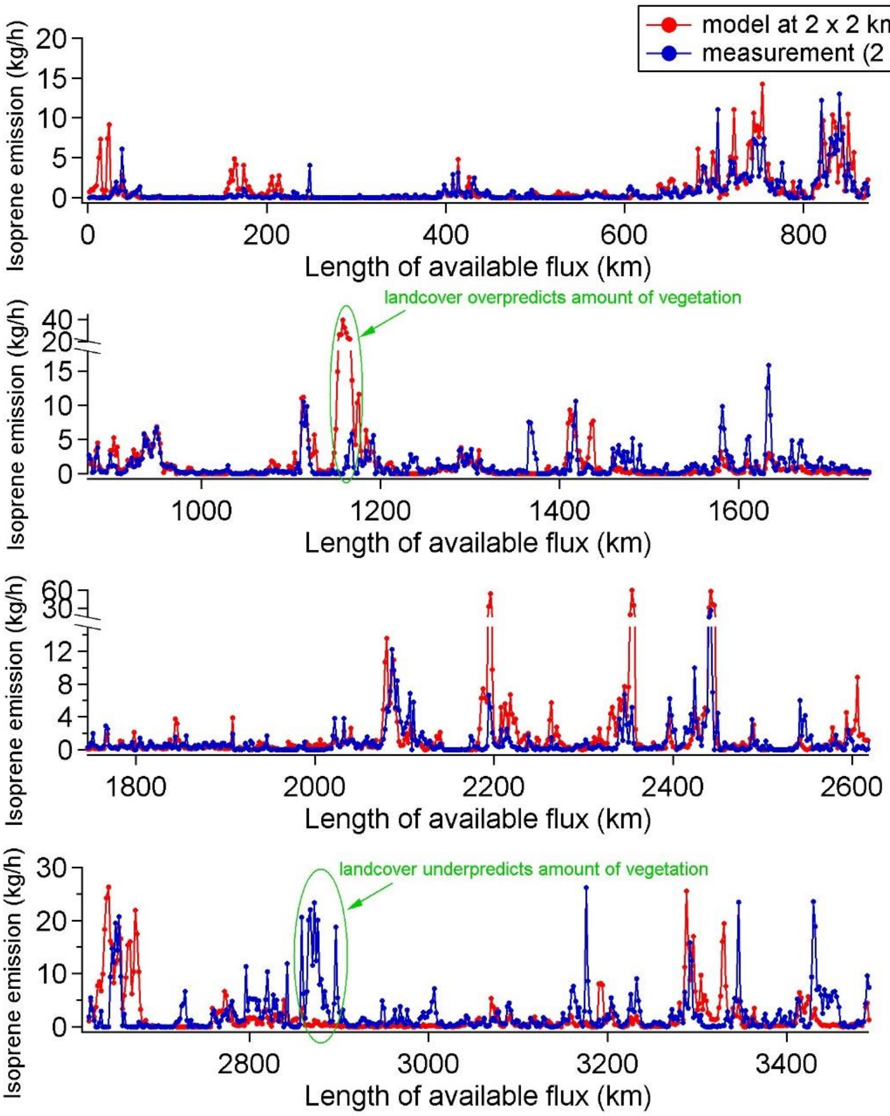


Figure S3. Time series for modeled and measured isoprene fluxes using the approximated circular footprint areas (only the data when flux was available are shown) along the full length of the flight tracks during the CABERNET campaign.

S4. The inverse G06 algorithm used in airborne emission factor derivation

In the original G06 algorithm (equation below), F_{G06} is the unknown, and BER is the known emission factor at standard temperature and PAR conditions. We inverse the equation so the BER is unknown and F is the airborne-derived surface flux. This BER is referred to as airborne basal emission factor (BEF) or just emission factor which represents the airborne flux inferred for the standard conditions of PAR=1000 μmol m^{-2} s^{-1} and temperature = 30 °C.

$$F_{G06} = \mathrm{BER} \cdot \underbrace{\mathrm{b}_3 \cdot \exp[\mathrm{b}_2 \cdot (P_{24} - P_0)] \cdot (P_{240})^{0.6} \cdot \frac{[\mathrm{b}_1 - \mathrm{b}_2 \ln(P_{240})] \cdot \mathrm{PAR}}{\sqrt{1 + [\mathrm{b}_1 - \mathrm{b}_2 \ln(P_{240})]^2 \cdot \mathrm{PAR}^2}}}_{\gamma_P} \cdot \underbrace{\mathrm{b}_5 \cdot \exp[\mathrm{b}_6 \cdot (T_{24} - 297)] \cdot \exp[\mathrm{b}_6 \cdot (T_{240} - 297)] \cdot \frac{\mathrm{C}_{T2} \cdot \exp\left[\mathrm{C}_{T1} \cdot \left(\frac{1}{T_{opt}} - \frac{1}{T}\right) \cdot \frac{1}{0.00831}\right]}{\mathrm{C}_{T2} - \mathrm{C}_{T1} \cdot \left[1 - \exp\left(\mathrm{C}_{T2} \cdot \left(\frac{1}{T_{opt}} - \frac{1}{T}\right) \cdot \frac{1}{0.00831}\right)\right]}}_{\gamma_T}$$

The micrometeorological variables include temperature close to the surface (T) and PAR. Previous 24 and 240-hour history of temperature and PAR are accounted for in T_{24}, P_{24}, T_{240}, P_{240} variables. The parameters of the algorithm were used as default (i.e. C_{T1}=95, C_{T2}=230, T_b=313, P_0=200, b_1=0.004, b_2 = 0.0005, b_3=0.0468, b_4=0.6, b_5=2.034, b_6=0.05).

Supplementary references:

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, 10.5194/gmd-5-1471-2012, 2012.