

Author's response to comments from Anonymous Referee #1:

"BVOC emission flux response to the El Niño-Southern Oscillation "

by Ryan Vella et al.

- 5 We thank editor and referees for taking the time to review our manuscript and for the valuable feedback. Here, the comments from Anonymous Referee #1 (from June 01, 2023) are reproduced in black, while our comments are presented in blue.

From Anonymous Referee #1's response:

- 10 In this study, the authors analyse potential links between climate variability induced by the El Niño Southern Oscillation and BVOC emission fluxes in a coupled GCM framework with interactive vegetation. They focus on different aspects of ENSO and the associated impacts on the terrestrial biosphere and BVOC emissions. The study is well written and presents interesting results, and I appreciate that the model runs must have been a huge effort to set up. However, I have some concerns that need to be addressed before the manuscript can be accepted for publication and included some general and specific
15 comments below.

Thank you for your positive comments. We acknowledge that the concerns raised here are valid and the recommended amendments greatly improved our manuscript. Please find our detailed responses below.

General comments

- 20 My major concern is the Results/Discussion section because the discussion is a bit thin. I might have miscounted, but there are only four references to contextualise the results! That's not enough for a discussion and I would like to see a more critical view on the model set up and outcomes in the study. I wonder whether it would help to split the results and discussion into two separate parts of the paper (but this is up to the authors).
- 25 We agree that the results presented in the submitted manuscript lacked a thorough discussion. The updated version has a separate section for the Discussion. The discussion compares our findings with several studies including the ones cited in the Introduction. More details are provided below, however, we invite the reviewer to refer to the updated manuscript.

Some things that could be discussed are:

- 30 You used a coupled simulation stressing the importance of land-atmosphere interactions but you don't really dig into describing processes that might influence the BVOC emissions (and how) except for the last sentence in the conclusions.

More details about the model setup and parametrisation of the BVOC emission module used are now provided in Section 2.2. We also mention this in the Discussion section. E.g.:

- 35 "The positive correlation between BVOC emissions and surface radiation could be explained by increased rates of photosynthesis, resulting in enhanced BVOC emissions from vegetation (Sharkey et al., 1996; Harley et al., 1999). It has recently been suggested that limited soil water access seems to influence isoprene emissions predominantly through growth stress and, to a lesser extent, closure of stomata, while monoterpene emissions are mostly restricted via stomatal closure (Bonn et al., 2019). Similarly,
- 40 temperature stress also substantially influences BVOC emission fluxes, as can be seen, e.g., by the power law functions of temperature in the description of isoprene emissions (Guenther et al., 2012). Areas with higher vegetation productivity tend to exhibit increased isoprene emissions as more carbon resources may be available for isoprene synthesis within actively growing vegetation. Higher LAI values indicate greater foliage density and, consequently, increased potential for isoprene production."
- 45 Has your coupled GCM set-up been evaluated and demonstrated to capture BVOC responses sufficiently compared to observations (if observations are available)?

- This study builds on the work by Forrest et al. (2020) and Vella et al. (2023); is is now mentioned in the updated manuscript. BVOC flux measurements are generally scarce and it is hard to constrain global budgets from measurements. However, our model setup has been evaluated against several global BVOC
- 50 emission models where it well-reproduced isoprene and monoterpene emissions. As the current model configuration does not include detailed land-use scenarios, the simulated vegetation corresponds mostly to "natural" vegetation only.

Details on this were presented in Vella et al. (2023), using the submodel ONEMIS (Kerkweg et al., 2006) in our modelling system EMAC (Jöckel et al., 2016) for biogenic emissions:

- 55 Isoprene
- Over the 10-year simulation period considered, the global annual total isoprene fluxes from ONEMIS were found to be 546 Tg yr⁻¹ (standard deviation (SD) = 8 Tg yr⁻¹) with dynamic vegetation and 558 Tg yr⁻¹ (SD = 7 Tg yr⁻¹) with climatological inputs. Jöckel et al. (2016) reported isoprene annual emissions of 488– 624 Tg using ONEMIS, while other studies estimated fluxes of 642 Tg yr⁻¹ (Shim et al., 2005) using 73 prescribed vegetation types, 571 Tg yr⁻¹ (Guenther et al., 2012) using inventories and Olson ecoregion land covers, 467 Tg yr⁻¹ (Arneth et al., 2007) using 10 PFTs from LPJ-GUESS and, more re- cently, 594 Tg yr⁻¹ using 16 PFTs (Sindelarova et al., 2014).
- 60

Monoterpenes

65 Annual totals from ONEMIS were found to be 102 Tg yr⁻¹ (SD = 1 Tg yr⁻¹) with dynamic vegetation inputs and 175 Tg yr⁻¹ (SD = 2 Tg yr⁻¹) with climatological inputs. MEGAN prescribes 54 Tg yr⁻¹ (SD = 0.7 Tg yr⁻¹) and 76 Tg yr⁻¹ (SD = 0.9 Tg yr⁻¹) with dynamic and climatological inputs, respectively. Guenther et al. (2012) gives a global annual monoterpene emission of 157 Tg, while Sindelarova et al. (2014) reported annual total emissions of monoterpenes ranging between 89 and 102 Tg yr⁻¹ over a 30-year simulation period. Arneth et al. (2007) reported 36 Tg yr⁻¹.

70 How do other land surface schemes model BVOC emissions and would you expect different results using a different LSM or GCM? Would you expect that your model framework is more suitable to address your research question compared to other coupled models that enable BVOC simulations?

75 Several Earth System Models (ESMs) and Chemistry-Climate Models (CCMs) employ similar algorithms, such as the Guenther algorithm (Guenther et al., 2012), to simulate Biogenic Volatile Organic Compounds (BVOC) emissions. While some variations exist, these schemes generally yield comparable results, with slight differences in the importance of input parameters, namely radiative fluxes, temperature, soil moisture, and vegetation. Therefore, it is crucial to accurately represent these parameters in the models.

80 Global scale models generally have a good representation of temperature and radiative fluxes. However, there are larger discrepancies among models when it comes to the hydrological cycle. Nevertheless, the EMAC model has demonstrated a good representation of the hydrological cycle, although it exhibits a moist bias at the southern edge of the Himalayas and a dry bias in Amazonia.

85 On the other hand, the representation of vegetation parameters (e.g., NPP, Leaf Area Index, leaf density) is less well-described, particularly in chemistry-climate models. Often, these parameters are either imported as climatological or observationally constrained datasets or described using highly simplified parameterizations. To address this weakness, some models have incorporated a dynamic vegetation model within the CCM, allowing for a fully interactive response of vegetation and its influence on BVOC emissions, even under varying climate conditions.

90 Consequently, our model framework enables the investigation of multiple aspects, extending beyond the scope of the presented study. Various ESMs incorporate atmosphere-land interactions, such as NorESM, EC-Earth, ECHAM, and UKESM. These models utilise the Guenther emission algorithms (e.g., MEGAN or similar) to estimate BVOC emissions. In our recent study (Vella et al., 2023), we demonstrated that our model setup is suitable for investigating land-atmosphere interactions through BVOC emissions. 95 Doubling CO₂ sensitivity experiments revealed that BVOC emissions from our model are sensitive to changes in vegetation and temperature. While some models include CO₂ inhibition on BVOC emissions (Arneth et al., 2007), the uncertainties surrounding this process remain high, and other studies suggest that CO₂ inhibition is not significant compared to the strong dependencies on temperature (Sun et al., 2013). In our setup, CO₂ inhibition on BVOC emissions is not included.

100

105 There is a wide range of estimates for global isoprene and monoterpene emissions in the literature. A recent study comparing NorESM, EC-Earth, and ECHAM revealed that NorESM has the lowest isoprene emissions at approximately 435 Tg yr^{-1} , while EC-Earth and ECHAM exhibit slightly higher emissions at 572 Tg yr^{-1} and 526 Tg yr^{-1} , respectively. Regarding monoterpenes, NorESM has the highest global emissions at 118 Tg yr^{-1} , followed by EC-Earth at 96 Tg yr^{-1} , and then ECHAM at 77 Tg yr^{-1} (Sporre et al., 2020). The models also show significant differences in aerosol radiative effects resulting from BVOC-SOA treatment, primarily due to different parameterizations and SOA treatments employed.

110 In conclusion, we have confidence in the robustness of our setup to study biosphere-atmosphere interactions arising from ENSO. However, we acknowledge that other model setups may capture these interactions differently. We hope that this study encourages further modeling efforts to evaluate such interactions.

Are there any caveats in the study itself or shortcomings in the model that could have inflated/ underestimated the results?

115 We highlight the fact that our approach has limitations as it simplifies the complexity of the climate system by disregarding the influence of other climate drivers that may interact with ENSO, for example feedbacks via chemistry, SOA, radiation, and aerosol-cloud interactions. We elaborate more on the fact that the Sustained ENSO simulations result in inflated BVOC emissions as they also capture long-term changes in the biosphere. However, these simulations are mostly intended for the statistical evaluation of the driving variables response to ENSO and the subsequent changes in BVOC emissions. Furthermore, 120 as mentioned above, the simulated vegetation does not include anthropogenic deforestation, such that the simulated vegetation patterns mostly resemble a potentially natural vegetation.

I want to stress that I don't expect detailed answers to all the questions above, they are just some suggestions for potential discussion points.

125 After reading the discussion and conclusions, it is not clear to me what the implications of the study are. By that I don't mean it the study set-up and results are not sufficiently interesting, but in my view the authors could expand more on the significance of their study in the current climate and future. i.e. if in fact ENSO events do become more sustained and/ or more extreme in a changing climate, you expect increased BVOC emissions. But what does that mean for associated processes in the atmosphere?

130 Now mentioned in the Conclusion: "As BVOC emissions are projected to rise in a warming climate, it becomes imperative to understand and quantify these disturbances to accurately predict future BVOC emissions, SOA formation, and their climate feedbacks. Additionally, BVOCs are crucial players in the formation of tropospheric ozone and other harmful air pollutants, posing risks to human health and regional air quality, especially in communities located close to dense forests. Furthermore, BVOCs can 135 act as precursors for greenhouse gases like methane, exacerbating the overall radiative forcing and contributing to climate change. Therefore, it is crucial to understand the intricate interplay between

ENSO, BVOC emissions, atmospheric chemistry, and climate for accurately predicting, and mitigating the far-reaching impacts of these ENSO in the climate system."

140 Your analysis relies on both isoprene and monoterpene emissions but the monoterpene emissions are largely neglected in the manuscript. Do the two types of emissions play different roles in the atmosphere or are they quite similar? You could pick this up in the discussion.

145 Monoterpenes were mostly not discussed in detail as their response to the factors driving emissions is similar to that of isoprene. In the ONEMIS parameterisations, the only differences between isoprene and monoterpene emission calculations is the emission factors used. We also explain why this could lead to differences, and also asymmetry in the isoprene and monoterpene emissions:

150 "In some regions, e.g., SEAsia (all scenarios except Moderate Niña) and the Amazon (Moderate Niña scenario), see Fig.7 & Fig. S5, we notice asymmetry in the isoprene and monoterpene emissions. The isoprene and monoterpene parameterisations in ONEMIS only differ in the emission factors and the correction factor based on the number of carbon atoms per molecule. This means that the different emission factors can lead to variations in the overall emission rates between the two compounds, even when other variables are the same. For example, if the emission factor for isoprene is assigned a higher weight compared to monoterpene, the model will amplify the effect of the corresponding variable (e.g., temperature) on isoprene emissions, resulting in a larger increase in isoprene fluxes compared to monoterpene fluxes. Conversely, if the emission factor for monoterpene is given a higher weight, the model will prioritize the effects of that variable, potentially leading to a larger decrease in monoterpene emissions compared to isoprene emissions."

160 In terms of atmospheric chemistry, oxidation products from monoterpenes are more likely to partition into the particle phase, but are emitted in much smaller quantities. Nevertheless, some plant types are more likely to emit isoprene whereas others are stronger sources of terpenes.

Specific comments

L1: It might be nicer to start with the umbrella term (BVOC emissions which is also in your title), and then divvy it up into isoprene and monoterpene emissions later on? But this is my personal preference and up to the authors.

165 Text now reads: "Emissions of Biogenic volatile organic compounds (BOVOCs) from the terrestrial biosphere play a significant role in major atmospheric processes."

L1: Can you give one example that explains the 'significant role' BVOC emissions play?

170 Yes, text updated: "BVOCs are highly reactive compounds that influence the atmosphere's oxidation capacity and also serve as precursors for the formation of aerosols that influence global radiation budgets."

L5: ENSO is the most important mode of climate variability and you could state this in the abstract to motivate your study

Now included in the abstract: "It perturbs the natural seasonality of weather systems on both global and regional scales and is considered the most significant driver of climate variability."

175 L35: Typo (?) 'The El Nino-Southern Oscillation (ENSO) is a periodic oscillation'

Typo fixed.

L58: Are there any assumptions that might explain the impact of ENSO on BVOC emissions in higher latitudes?

180 ENSO does not only affect the low latitudes, but via global teleconnection patterns, also alters the meridional temperature gradient and precipitation patterns, even in Europe (Martija-Díez et al., 2023). Consequently, ENSO has to be regarded as a global scale phenomenon, though the impact in the low latitudes is substantially stronger.

185 With reference to the cited study, Müller et al. (2008) found correlations of ONI with isoprene emissions over higher latitudes (correlation coefficient between -0.3 and 0.3) especially when a 6-month shift was applied. The study does not go into details on the assumptions that might explain the impact of ENSO on BVOC emissions in higher latitudes, however, BVOC fluxes in higher latitudes are generally low so the impact on anomalies should not be so significant. This is also why in this study we focus on regions close or in the tropics.

190 L83-84: The citations are a bit off - 'aerosol-cloud interactions (e.g. Tost, 2017). In this study, version [...] used in comprehensive model intercomparison studies (e.g. Joeckel et al., 2016)'

The citations used here have been selected to describe the comprehensive modelling system and to show potential of follow-up studies using the interactive BVOC emissions.

L87: Could define LPJ-GUESS in the first line of the section (L86, sorry for being pedantic)

195 Now defined in the first line.

L96: Why did you exclude land-use change? The use of PNV could also be a discussion point

This is a limitation of or current model setup. The new version of LPJ-GUESS will include land use functionality. Now clarified in manuscript.

200 L98-105: You very superficially describe the different components of the model, fair enough – but given this study is focussed on the BVOC it'd be nice to know if there is one core process or something that describes the BVOC module and how it links land surface and atmosphere in your model set up.

More details about the model coupling and the BVOC emission module were provided in Section 2.2.

205 "While efforts for a fully coupled configuration are ongoing, in this work, we use the standard EMAC-LPJ-GUESS coupled configuration, where the vegetation in LPJ-GUESS is entirely determined by the EMAC atmospheric state, soil, N deposition, and fluxes (Forrest et al., 2020). After each simulation day EMAC computes the average daily values of 2-meter temperature, net downwards shortwave radiation, and total precipitation and passes these state variables to LPJ-GUESS. Vegetation information (LAI, foliar density, leaf area density distribution, and PFT fractional coverage) from LPJ-GUESS is then fed back
210 to EMAC for the calculation of BVOC emission fluxes using EMAC's BVOC submodules (Vella et al., 2023), namely ONEMIS (Kerkweg et al., 2006) and MEGAN (Guenther et al., 2006). Both ONEMIS and MEGAN are based on the Guenther algorithms (Guenther et al., 1993), where the BVOC emission flux (F) is calculated as a function of the foliar density and its vertical distribution (D [kg dry matter m^{-2}]), ecosystem-specific emission factors (ϵ), and a non-dimensional activity factor (γ) that accounts
215 for the photosynthetically active radiation (PAR) and temperature:

$$F = [D] [\epsilon] [\gamma] \tag{1}$$

In this work, we evaluate fluxes from ONEMIS, which is the standard and most established emission module in EMAC. Emissions are calculated at four distinct canopy layers, which are defined by the leaf area density (LAD) and the leaf area index (LAI). The attenuation of the PAR is determined for
220 each level by considering the direct visible radiation and the zenith angle. Using the proportions of sunlit leaves and the overall biomass, emissions from both sunlit and shaded leaves within the canopy are estimated. Further technical details for canopy processes employed in ONEMIS can be found in Ganzeveld et al. (2002). While validating pure BVOC fluxes from models using observations remains challenging, this setup was evaluated and demonstrated to well-capture global BVOC estimates and
225 responses when compared to other modelling studies (Vella et al., 2023). As described in Eq. 1, BVOC emission calculations in this setup are governed by vegetation states (D) from LPJ-GUESS that are largely based on temperature, radiation, and soil moisture. Furthermore, the instantaneous surface radiation and temperature levels (γ) have a large impact on the emission rates. On the the basis of such model parameterisations, we explore the impact on BVOC emission anomalies by evaluating changes in the
230 surface temperature and radiation, the aridity index (AI), the NPP, and the LAI."

L107: Have you defined AMIPII somewhere?

Now defined.

L111: Are your thresholds defining weak, moderate and strong common practice? I.e. can you support this decision with a citation pointing to other research using the same thresholds?

235 There is no officially published thresholds, however, these are used by NOAA and also in several publication. Now explained in Section 2.3.

240 "Even though not officially published, this ONI threshold classification has been used by the National Oceanic and Atmospheric Administration (NOAA) (www.climate.gov/news-features/blogs/enso/united-states-el-niño-impacts-0, last access: 03 July 2023) and also in several research articles (e.g., Jimenez et al., 2021; Abish and Mohanakumar, 2013)."

L125: Not sure I understand the last sentence on the page. Are you saying you chose the seven regions because they are mostly in the tropics which are typically areas with high BVOC emissions (can you include a reference to support this statement)? You could further motivate the choice of regions by mentioning that they conveniently happen to be ENSO hotspots as well (except NE Australia)

245 This is now mentioned as follows: "The regions considered are hotspots for ENSO (apart from NE Australia) and places with generally high BVOC emissions in the tropics (except from SW USA) (Bastos et al., 2013; Vella et al., 2023; Sindelarova et al., 2014). Additionally, we used the BVOC anomaly distribution maps (Fig. 7) to establish the exact dimensions of the bounding box for regions with relatively consistent BVOC anomalies."

250 L129: Have you defined the 'base conditions' somewhere?

Now defined in Section 2.3

L132: Does this mean that in the 31st and 32nd year you perturb the atmospheric circulation with your ENSO anomalies?

Yes. Text amended.

255 L142: Typo - 'Even though'

Fixed, thank you.

L151: Could you write out Jan and Dec to January and December please:)

Now written in full.

L151: Capital Event?

260 Fixed.

L167: A bit convoluted.. Maybe something like 'however, following the ENSO perturbation fluxes diverge'

Updated.

L189: The definition of the aridity index belongs in the methods section

265 Moved to Section Section 2.3.

L190: Throughout your manuscript you're not consistent with italic/ not italic 'base' scenarios/ conditions

Italics were removed completely. Now the scenarios are consistently referred to as "base", "Moderate" and "Very Strong" El Niño/La Niña.

270 L191: Are r-values the correlation coefficients?

Yes, updated.

Table 2: I like that you give both percentage and absolute changes for temperature in Table 2 to get a sense of magnitude. Can you also include the actual values for change in Radiation and AI in the table? It might make it easier to link the table to Figure 4.

275 All tables now include absolute an % changes.

Figure 3: I think the figure is very small and it's quite hard to see anything on it. Maybe you could rearrange the panels. There is also a lot of white space at the top that maybe could be trimmed? But maybe I just can't see the datapoints. Could you spell out the abbreviations in the caption too (AI, NPP, LAI)?

280 The panels were rearranged to make them bigger. Looks better now. Abbreviations in the figure captions are spelled out.

Section 3.2.1. is a description of the results – where is the discussion here? For example, are the anomalies shown in Figure 4 what you expect [. . .]? As I said above, it might be easier to split results and discussion but that is up to you.

285 This is now discussed in the separate Discussion Section.

"It has been suggested that changes in weather patterns during ENSO events are linked to the re-arrangement of the Walker circulation convective centers and teleconnections with midlatitude westerlies (McPhaden et al., 2006; Dai and Wigley, 2000). Our simulations agree with previous studies suggesting that during El Niño the tropics become warmer and drier (Gong and Wang, 1999; Dai and Wigley, 2000), while some areas such as Western North America and East Asia tend to be cooler and wetter (Ropelewski and Halpert, 1986; Wu et al., 2003). Bastos et al. (2013) investigated the variations in temperature, radiation, and precipitation during El Niño and La Niña events from 2000 to 2011 and revealed significant changes in these climatic factors. Positive temperature anomalies exceeding 1 °C were observed in the Amazon, Central and South Africa, and northern Australia during El Niño, while cooler temperatures were detected in the USA and Europe. In our study, we also observed similar trends, with the strong signal over Australia coming from the significantly cooler temperatures during La Niña. However, we did not observe such a pronounced influence on European temperatures. Furthermore, our results align with the findings of Bastos et al. (2013) in terms of surface radiation changes. Regarding precipitation, the signal in Bastos et al. (2013) was less distinct, but a decrease in precipitation in the Amazon region during El Niño was suggested. Consistent with these findings, our study revealed higher aridity in the Amazon, supporting the notion of decreased precipitation in this region during El Niño events."

Figure 4: I appreciate the value of including anomalies over the ocean as the temperature and radiation plots show the typical ENSO anomalies over the ocean quite nicely. However I wonder, given this study is mostly focussed on land processes, whether you would consider to mask the ocean and include a supplementary figure of the SST anomalies to demonstrate that your experiment captures ENSO. Especially for the radiation anomalies, it is quite hard to see what's happening for the majority of the land surface because the colorbar is maxed out to fit to the ocean anomalies. In this figure, I'm surprised that the bottom panels do not show a signal in Australia which pops up as one of the most impacted regions in Figure 5. Does the water limitation signal disappear because you use the aridity index here rather than direct precipitation anomalies? None of the other anomalies seem to be able to explain the strong signal.

All figures now updated with an ocean mask to make anomalies on land clearer. The SST plot that depicts ENSO conditions is included in the supplement.

Thanks for noting the abnormal signal over Australia in Fig. 5. LPJ-GUESS tends to assign very tiny, but non-zero, values over regions without vegetation. We usually apply a small threshold to discard such values over desert regions. I checked my code and realised that this threshold was being applied after

320 the two-tailed Student's t-test. So the "significant correlation" shown was actually coming from these tiny insignificant values. Once the thresholds are applied properly this signal over Australia disappears. See updated Fig. 5.

L219: You use the abbreviation SEASIA here but in Table 2 for example it is SEAsia. I'm not sure whether this happening in other places in the manuscript, but can you make sure you are consistent within the manuscript?

325 SEASIA is a typo. All consistent now.

Figure 5: I'm a bit surprised about this figure but maybe I'm misreading it. The middle panels contrast vegetation anomalies in an extreme El Nino with that of an extreme La Nina right? The patterns almost look identical, especially for NPP, and I had to zoom in to see that they the top middle and right panel are not identical but show small differences in the hatching. I wonder whether there might have been a mistake in the plot. Typically for an extreme El Nino, you would expect a negative signal at least for parts of Australia due to increased water limitation while for a La Nina it would be positive as you show here. I also would have expected a negative signal in the tropical rainforests in South America and South East Asia. Figure 4 shows a somewhat contrasting signal in the Aridity Index and to some degree in the incoming SW radiation (but it's hard to tell due to the colorbar, see comment above). Can you confirm that Figure 5 indeed shows the 'correct' distribution of anomalies, and if so can you explain the signal given it is quite counter-intuitive?

340 Fig. 5 shows the spatial distribution of NPP and LAI as well as the El Niño anomaly (El Niño – Base conditions) and La Niña anomaly (La Niña – Base). There was indeed a bug in the script for this plot, where the differences were not calculated properly. The updated plots are coherent with your remarks about El Niño / La Niña effects on vegetation. The colour scheme was also updated to shades of blue and red as this better depicted the anomaly distributions.

L.234-235: Can you rephrase this? Nearly instantaneously and rather quickly sound like quite similar timescales to me. Are you showing the lag in vegetation response somewhere? If so can you point the reader to that information? If this is meant to be a more general discussion point, could you include a reference to support this statement?

350 Rephrased to "rather slowly". We do not explore vegetation lags in detail here and this a more general comment to emphasise the changes seen in Fig. 6. As the model formulation allows for new establishment of PFTs only at the end of the year (see the LPJ/GUESS description for more details), some changes in vegetation distribution patterns show a longer lag in the corresponding emission driving parameters compared to the direct response of e.g., soil water stress.

L263: I probably just missed it, but where did you mention before that the emission changes may be exaggerated? I think this could be a good discussion point, can you unpack this more?

Emissions from the Sustained simulations may be exaggerated in the sense that they include long term changes in the vegetation. More clearly mentioned now.

355 L279: What does this mean – high NPP and LAI = high isoprene emissions?

Yes, this means that higher NPP and LAI results in more BVOC emissions.

L271-284: Following this section, you define 'strong correlations' as values greater than 0.4? Often correlation coefficients are split into weak/moderate/strong classes, and values around 0.5 would typically considered moderate. I think you should be more careful with your phrasing here and/or define somewhere
360 where your differentiation is coming from (based on significance?). You do need to be consistent with the actual values of the correlation coefficients though; the ones in written in the text do not always match the ones in the figure (small differences only).

We are now consistent throughout by using the following classification: 0.00-0.29 as negligible, 0.30-0.49 as weak, 0.50-0.69 as moderate, 0.70-0.89 as strong, and ≥ 0.90 as very strong for positive correlations
365 and similarly for negative correlation between 0 and -1.

L289-295: You found relationships based on a Pearson correlation, but you don't explain why temperature anomalies drive isoprene fluxes in Africa, and LAI in the southern USA, north east South America, South Africa, Central Asia and Australia. Is this a surprising result? Is it what you expected? Do you know why this is emerging from the model?

370 The dependencies from the correlation analysis are discussed in the Discussion section.

These dependencies are complex but can be associated with the magnitude in the anomalies of the driving variables as well as how different plant species within a specific microclimate respond to such changes. For example, in Central Africa during El Niño, we have a strong positive temperature anomalies,
375 but anomalies in surface radiation and aridity are not so great (see Fig. 4). This observation potentially elucidates why temperature serves as the primary driver of BVOC anomalies in this particular area. On the other hand, in northeast South America, we observe a substantial impact on temperature, accompanied by significant alterations in surface radiation and AI. These combined effects likely contribute to the robust signal in net primary productivity (NPP) and, more specifically, to the changes observed in
380 leaf area index (LAI) in this region.

Our findings indicate that in the southern USA, northeast South America, South Africa, Central Asia, and Australia, BVOC anomalies are primarily influenced by changes in leaf area index (LAI) resulting from the adaptation of vegetation to new climate states. Although LAI is inherently influenced by atmospheric conditions, the prolonged alterations in LAI resulting from changes in precipitation patterns,
385 temperature, and radiation regimes associated with sustained ENSO conditions have a significant impact

on BVOC emissions. It is important to note that the changes presented in this study do not account for anthropogenic influences, such as land-use changes, deforestation, and increasing CO₂ concentrations which would also influence the response of the biosphere and BVOC emissions.

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Boreal forests, at higher latitudes, are typically characterised by colder climates with shorter growing seasons. In these regions, the availability of sunlight, represented by surface radiation, plays a crucial role in determining photosynthetic activity and plant growth. Changes in surface radiation, such as alterations in cloud cover or atmospheric conditions, can directly impact the amount of solar energy reaching the vegetation canopy. Increased surface radiation can enhance photosynthesis and, subsequently, BVOC emissions in boreal forests, where plants are sensitive to changes in light availability.

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L312: Your current data availability statement is not sufficient for Earth System Dynamics. You should at least make your analysis code publicly available. For the time being I'm sure a github link (or similar) will be enough but for publication you will be asked to publish a zenodo link anyway so you might as well get started on that now!

400

Data and analysis code will be made available on zenodo. Model code could not be made public.

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"BVOC emission flux response to the El Niño-Southern Oscillation "

by Ryan Vella et al.

- 5 We thank editor and referees for taking the time to review our manuscript and for the valuable feedback. Here, the comments from Anonymous Referee #2 (from June 05, 2023) are reproduced in black, while our comments are presented in blue.

From Anonymous Referee #2's response:

10 In this article the authors explore the impacts of ENSO on modelled emissions of biogenic volatile organic compounds (BVOCs). The article is well written and this is an interesting study, which is certainly within the scope of the journal, but should only be published after the following comments have been addressed.

15 My major concern is with regards to Section 3 (Results and Discussion). In the absence of a dedicated "Discussion" section I would have expected to see more analysis and comparison to the wider literature alongside the presentation of the results. In the Introduction, several studies are cited that have used observations to explore the links between ENSO and the biosphere – how do your model results compare to what they found? This is an interesting study and should be published but without some more context the reader is left to do a lot of work themselves to understand the implications of these results.

20 Thank you for considering this study for potential publication in BG. We acknowledge the lack of discussion in the submitted version. We now included a dedicated Discussion Section that compares our results with several studies, including those cited in the Introduction. Below is some text from the new Discussion section. We invite the reviewer to check out the updated version of the manuscript for further details.

25 "The BVOC emission anomalies from our isolated simulations agree with previous work linking high BVOC emissions with El Niño years (e.g., 1983, 1987, 1990–1991 and 1994–1995), and lower emissions with La Niña years (e.g 1984–1985, 1988–1989) (Lathiere et al., 2006; Naik et al., 2004). With CO₂ concentrations fixed to 1983, it was shown that isoprene emissions are higher (1.92%) during El Niño years and lower (–0.63%) during La Niña years compared to the 1983–1995 average (Lathiere et al., 2006). Our simulations, based on 1997/98 (Very Strong El Niño) and 1988/89 (Very Strong La Niña),
30 suggest an increase (2.9%) and a decrease (–0.1%) for El Niño and La Niña, respectively. The variances

could arise from differences in the model configurations and the fact that the time frames for "base conditions" differ."

Minor Comments:

Section 1 (Introduction):

35 Could you expand slightly on the statement you make about future changes in ENSO: "several studies have suggested the possibility of more persistent ENSO conditions in the future (e.g. Bacer et al., 2016; Cai et al., 2015)" - does this mean more frequent, longer lasting, more extreme etc? You can then come back to this in your later Discussion to help the reader understand the implications of your results.

40 This statement in the Introduction was updated as follows: "some studies have suggested the possibility of increased frequency of extreme ENSO events under greenhouse warming (e.g. Cai et al., 2015, 2021)." This means that ENSO events are expected to occur more often with bigger intensities, but not necessarily longer lasting.

Section 2.2:

45 Can you justify the use of BVOC fluxes from ONEMIS (rather than MEGAN) if they are the only emissions used here.

50 Both ONEMIS and MEGAN could have been used for this study. We decided to use ONEMIS here as this module is the standard and more established emission model in EMAC. ONEMIS has been integrated in EMAC and used for a long time and thus BVOC emissions from ONEMIS could be compared with previous studies. Additionally, the current MEGAN version in EMAC uses the parameterised canopy environment emission activity (PCEEA) algorithm (only considering above-canopy photosynthetic photon flux density) rather than the alternative detailed canopy environment model that calculates light and temperature at each canopy depth. On the other hand, in ONEMIS, emissions are calculated within four distinguished layers of the canopy. In Vella et al. (2023), we found some artifacts in the BVOC emissions from MEGAN resulting from the PCEEA. For example, in dense forests, higher LAI (e.g. from increased temperature) at the top of the canopy could result in more shade in the lower parts of the canopy, resulting in a net decrease in BVOC emissions.

Section 2.3:

60 The description of the simulation set up for the isolated scenarios is clear in that base conditions are used throughout the 50 years but with an isolated El Nino / La Nina in years 31-32. It would be useful to add some clarification on what the base conditions are, you mention using the SST/SIC data as forcing data to construct the El Nino / La Nina scenarios but it's not clear what is used for the non El Nino / La Nina years. It is later mentioned in the description of the sustained simulations but needs articulating sooner and in addition to temperature, what time period do the CO2 concentrations represent? Could you also add here clarification of what happens in the year following the isolated El Nino / La Nina.

65 Thanks for pointing this out. Section 2.3 was updated and now clearly states what we mean by "Base conditions" i.e. SST/SIC average from 1980-2009. It is also mentioned that we keep CO₂ concentrations fixed to 348 ppmv, representing the year 2000.

Section 3.1:

70 It may be beyond the scope of this paper to demonstrate this here but can you be satisfied that your modelling set up captures the observed relationships between e.g., temperature, radiation and BVOC emission fluxes. You can refer to other studies to support this but at the moment the reader is expected to assume that this is the case.

Our results are in good agreement with most studies out there in the ENSO-induced changes for temperature, radiation, NPP, LAI, and BVOC emissions. This is now discussed in the Discussion Section.

75

"The changes in temperature, surface radiation, and AI during El Niño and La Niña events can have significant impacts on vegetation, as reflected in the changes in NPP and LAI shown in Fig. 5 and Table 4. Our findings are consistent with previous studies linking low global NPP to El Niño years and high global NPP to La Niña years (Zhang et al., 2019; Bastos et al., 2013; Nemani et al., 2003; Behrenfeld et al., 2001). Higher temperatures lead to higher evapotranspiration rates and increased water stress on vegetation, which may result in reduced NPP and decreased LAI. Cooler temperatures can have varying effects on vegetation, depending on the specific ecological conditions of the region. However, increased surface radiation can enhance photosynthesis and potentially lead to higher NPP. The positive anomalies in NPP observed during La Niña in several regions, such as SWUSA, SEAsia, and NEAus, may be attributed to the combined effects of cooler temperatures and increased radiation. "

85

It would be interesting to understand the difference between the relationships depicted in Figure 3 for the two years during the isolated El Niño / La Niña (green years) and the two years following (yellow years). I.e., which of these variables is driving the change in BVOC emissions once the initial temperature perturbation has gone away, does it change?

90 We included a new table (Table 2) showing correlations between driving variables and isoprene fluxes: 1) during the event, 2) in the two years following the event, and 3) both time-frames (4 years). This allowed us to discuss in more detail the effect of the driving variables. We found that climatic variables tend to correlate more strongly during the event while the vegetation variables also correlate quite well in the two years following the event, suggesting a longer lasting signal from vegetation.

95 Section 3.2:

Can you add some clarification to the captions for the Figures and Tables in this section as to the time period that the changes correspond to. From the Methods section I think these must be 30-year means

following 20 years of sustained El Nino / La Nina but it would be useful to state that here (especially if my interpretation is not correct!)

100 Your interpretation is correct. The captions are updated to clarify this point.

In the scenarios that see an increase in total vegetation coverage, do you know which land cover type is being lost? I.e., what is the vegetation expanding into?

105 After checking the total vegetation coverage in the areas considered, it became clear that there are patches of land missing vegetation (even in areas including dense forest such as the Amazon). As seen in Fig 6. some PFTs expand while others shrink, however it could also be the case that the total vegetated area increases as it expands into these "empty" patches. A sentence was included to explain this.

Editorial Comments:

Page 2, line 30: correct "oxidant"

Page 3, line 70: correct "us" to "use"

110 Page 6, line 142: correct "Event"

Page 9, line 192, should "start" be "star"?

Page 12, line 237: should "vegetational" be "vegetation"? (I would change this throughout but could leave for Copernicus Copy Editor's opinion)

Supplement:

115 Page 1: correct spelling of Table in Fig S1 caption

Manuscript updated accordingly. Thank you.

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Author's response to comments from Anonymous Referee #3:

"BVOC emission flux response to the El Niño-Southern Oscillation "

by Ryan Vella et al.

- 5 We thank editor and referees for taking the time to review our manuscript and for the valuable feedback. Here, the comments from Anonymous Referee #3 (from June 05, 2023) are reproduced in black, while our comments are presented in blue.

From Anonymous Referee #3's response:

Reviews for "BVOC emission flux response to the El Nino-Southern Oscillation"

- 10 Isoprene and monoterpene emissions from the terrestrial biosphere play a significant role in major atmospheric processes. Biogenic volatile organic compound (BVOC) emissions are sensitive to climatic influences. This manuscript attempts to understand the relationship between BVOC emission and ENSO events using a global atmospheric chemistry-climate model with enabled interactive vegetation. Overall, the results are reasonable, and I recommend a major revision before acceptance.
- 15 [Many thanks for considering our manuscript for review in BG. Detailed response below.](#)

Major comments:

(1) In Section 2.2 EMAC-LPJ-GUESS configuration, I prefer that you can list some key equations for the parameterizations of BVOC emissions in this study. So we can easily understand why you choose temperature, radiation, AI, NPP, and LAI to investigate their impacts on BVOC emission anomalies.

- 20 [Section 2.1 was extended and now includes more details on the model configuration. Also included the key formula for the BVOC parameterisation in ONEMIS. We explain why we evaluate temperature, radiation, AI, NPP, and LAI to study changes in BVOC emissions.](#)

- 25 ["While efforts for a fully coupled configuration are ongoing, in this work, we use the standard EMAC-LPJ-GUESS coupled configuration, where the vegetation in LPJ-GUESS is entirely determined by the EMAC atmospheric state, soil, N deposition, and fluxes \(Forrest et al., 2020\). After each simulation day EMAC computes the average daily values of 2-meter temperature, net downwards shortwave radiation, and total precipitation and passes these state variables to LPJ-GUESS. Vegetation information \(LAI, foliar](#)

density, leaf area density distribution, and PFT fractional coverage) from LPJ-GUESS is then fed back to EMAC for the calculation of BVOC emission fluxes using EMAC's BVOC submodules (Vella et al., 2023), namely ONEMIS (Kerkweg et al., 2006) and MEGAN (Guenther et al., 2006). Both ONEMIS and MEGAN are based on the Guenther algorithms (Guenther et al., 1993), where the BVOC emission flux (F) is calculated as a function of the foliar density and its vertical distribution (D [kg dry matter m^{-2}]), ecosystem-specific emission factors (ϵ), and a non-dimensional activity factor (γ) that accounts for the photosynthetically active radiation (PAR) and temperature:

$$F = [D] [\epsilon] [\gamma] \quad (1)$$

In this work, we evaluate fluxes from ONEMIS, which is the standard and most established emission module in EMAC. Emissions are calculated at four distinct canopy layers, which are defined by the leaf area density (LAD) and the leaf area index (LAI). The attenuation of the PAR is determined for each level by considering the direct visible radiation and the zenith angle. Using the proportions of sunlit leaves and the overall biomass, emissions from both sunlit and shaded leaves within the canopy are estimated. Further technical details for canopy processes employed in ONEMIS can be found in Ganzeveld et al. (2002). While validating pure BVOC fluxes from models using observations remains challenging, this setup was evaluated and demonstrated to well-capture global BVOC estimates and responses when compared to other modelling studies (Vella et al., 2023). As described in Eq. 1, BVOC emission calculations in this setup are governed by vegetation states (D) from LPJ-GUESS that are largely based on temperature, radiation, and soil moisture. Furthermore, the instantaneous surface radiation and temperature levels (γ) have a large impact on the emission rates. On the the basis of such model parameterisations, we explore the impact on BVOC emission anomalies by evaluating changes in the surface temperature and radiation, the aridity index (AI), the NPP, and the LAI."

(2) Lots of sentences in the main text should appear in the figure captions. Please revise them through the whole text. For example, Page5 Line117-118, "The base year (ie. The 30-year average SST Blue (La Nina)." should be placed in the Figure 1 caption. Page 9 Line 191-192 "The r value for each grid is shown and correlations with $p < .01$ are marked with a start sign" should be placed in the Figure 3 caption.

All figure caption were updated accordingly.

(3) Page 8 Line 176-177 "During El Nino and the subsequent two years, SWUSA experiences a rise of 15.6% and 14.3%, respectively, while a decline of 24.4% is found in SWUSA during the two years following La Nina". The responses seem to be asymmetrical for El Nino and La Nina. So why the response of BVOC to La Nina has the lowest decline in the following two years?

If we look at the driving variables over SWUSA, we see asymmetrical responses during El Niño and La Niña e.g., warmer and cooler surface temperatures, higher NPP/LAI and lower NPP/LAI during El Niño and La Niña, respectively (see Fig. 4 & 5). These changes could explain the response of BVOC emissions

- higher during El Niño because of higher temperatures and elevated NPP/LAI, lower during La Nina because of cooler temperatures and lower NPP/LAI.

65 We added a new table (Table 2) that shows the correlations during and following the event, separately. During La Nina in SWUSA, we see a moderate-to-strong correlations between the isoprene flux and the NPP, LAI, and AI (especially with NPP/LAI in the following 2 years), but not so much with the temperature and srface radiation. Therefore, the response of BVOC to La Niña has the lowest decline in the following two years because of ENSO-induced anomalies in the vegetation states with longer-lasting
70 effects.

Furthermore, even though the emission fluxes depend on several input parameters, their sensitivity across the occurring values is not linear, such that even though La Niña shows cooler temperatures (and therefore not that much heat stress) without significantly reduced NPP and LAI as a direct response,
75 the decline in the emissions is weaker than the increase during El Niño.

(4) English writing need to be improved further.

The manuscript was sent to a professional proofreader. We hope that it reads better now.

Some minors:

(1) Page 1 Line 1: “major atmospheric processes”, could you show one or two specific examples.

80 Updated.

(2) Page 2 Line 45-46: “Several studies explored the sensitivity of the terrestrial biosphere to different ENSO phases (e.g. Ahlstrom et al., 2015; Chang et al., 2017; Bastos et al., 2018; Teckentrup et al., 2021)”, here is another paper well suitable here. See “Wang, J., Zeng, N., Wang, M., Jiang, F., Chen, J., Friedlingstein, P., Jain, A. K., Jiang, Z., Ju, W., Lienert, S., Nabel, J., Sitch, S., Viovy, N., Wang, H., and
85 Wiltshire, A. J.: Contrasting interannual atmospheric CO2 variabilities and their terrestrial mechanisms for two types of El Ninos, Atmos. Chem. Phys., 18, 10333-10345, 2018.”

Citation was added.

(3) Page 6 Line 142: “give realistic insights on changes” => give insights into changes. I think simulated results are not necessarily “realistic”.

90 Updated.

(4) Page 10 Line 210: “. . . anomalies from very strong El Nino and La Nina scenarios”, the results in Figure 4 is composite results?

95 Fig. 4 shows results from the sustained ENSO scenarios. On the left hand-side we show the spatial distribution of the variables in "base conditions" i.e. using climatological SST/SIC (1980-2009), while in the middle and right-hand side we show anomalies by comparing simulations with sustained El Niño / La Niña SST/SIC with the "base" simulation.

The sentence was updated as follows:

100 "Fig. 4 shows global distributions of surface temperature, net solar radiative flux at the surface, and the AI averaged over 30 years for the base scenario as well as anomalies from Very Strong El Niño (Very Strong El Niño – Base) and La Niña (Very Strong La Niña – Base) scenarios."

(5) Page 13 Line 240-244: Two sentences are duplicate.

Fixed, thank you.

(6) Page 13: "TeBe" => "TeBE"

105 Updated.

(7) Page 14 Line 262-263: "statistically significant anomalies only occur in the very strong El Niño scenario with and increase from 34.13 Tg yr-1 to 38.13 Tg yr-1 (+11.72%) from base scenarios to very strong El Nino" => statistically significant anomalies only occur in the very strong El Niño scenario with the increase from 34.13 Tg yr-1 during the base scenarios to 38.13 Tg yr-1 (+11.72%) during the
110 very strong El Nino.

Updated.

(8) Figure 8 figure caption: The Person's correlation => The Pearson's correlation

Updated

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