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The influences of El Niño–Southern Oscillation on tropospheric ozone in CMIP6 models

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Abstract. Ozone in the troposphere is a greenhouse gas and a pollutant, hence, additional understanding of the drivers of tropospheric ozone evolution is essential. The El Niño–Southern Oscillation (ENSO) is a main climate mode and may contribute to the variations of tropospheric ozone. Nevertheless, there is uncertainty regarding the causal influences of ENSO on tropospheric ozone under warming environment. Here, we investigated the links between ENSO and tropospheric ozone using Coupled Modeling Intercomparison Project Phase 6 (CMIP6) data over the period 1850-2014. Our results show that ENSO impacts on tropospheric ozone are primarily found over oceans, while the signature of ENSO over continents is largely nonsignificant. The response of ozone to ENSO may vary depending on specific air pressure levels in the troposphere. These responses are weak in the middle troposphere and are stronger in the upper and lower troposphere. Although there are biases in simulating the signature of ENSO on surface ozone, these signatures in the middle and upper troposphere appear to be more consistent across CMIP6 models. While the response of tropical tropospheric ozone to ENSO is in agreement with previous works, our results suggest that ENSO impacts on tropospheric ozone of the mid-latitude regions over the southern Pacific, Atlantic, and Indian oceans might be more significant than previously understood.

Keywords: El Niño–Southern Oscillation; historical simulations; tropospheric ozone; biogeochemistry; CMIP6.

1 Introduction

Ozone in the troposphere is an important greenhouse gas and pollutant (Archibald et al., 2020; Cooper et al., 2010; Wang et al., 2022). Tropospheric ozone has detrimental effects on human health and ecosystems (Fleming et al., 2018; Franz et al., 2018; Gaudel et al., 2020; Lu et al., 2019; Oliver et al., 2018; Peron et al., 2021; Roberts et al., 2022; Schauberger et al., 2019). Changes in atmospheric ozone may also affect radiative forcing and have effects on climate (Gauss et al., 2006; Myhre et al., 2013).

The El Niño–Southern Oscillation (ENSO) is the major mode of climate variability with global impacts (Bjerknes, 1969; Cai et al., 2020; McPhaden et al., 2006) and is expected to affect variations of global tropospheric ozone. ENSO-induced changes in climate and meteorological conditions (Le and Bae, 2022; Lu et al., 2019; Yeh et al., 2018) lead to impacts on ecosystems and the production/removal of ozone in soil, plant, and the water cycle, and the transport of ozone (Ganzeveld et al., 2009; Lin et al., 2019; Neu et al., 2014). In particular, ENSO drives changes in tropospheric and stratospheric

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circulations which can alter the tropospheric ozone variations (Daskalakis et al., 2022; Domeisen et al., 2019; Koumoutsaris et al., 2008; Lin et al., 2015; Neu et al., 2014; Olsen et al., 2019; Oman et al., 2013; Zeng and Pyle, 2005; Ziemke et al., 2015). In addition, ENSO was revealed to exhibit influences on tropospheric ozone concentrations in many regions by modulating local meteorological conditions (Doherty et al., 2006; Jiang and Li, 2022; Oman et al., 2011; Peiro et al., 2018; Rowlinson et al., 2019; Wie et al., 2021; Xu et al., 2017; Yang et al., 2022; Zhang et al., 2015).

Nevertheless, there are uncertainties regarding the causal effects of ENSO on global tropospheric ozone. For instance, while the response of tropospheric ozone to ENSO over the mid-latitude regions remains elusive (Lu et al., 2019; Olsen et al., 2016), further understanding of ENSO impacts on ozone concentrations at multiple air pressure levels in the troposphere is necessary. Despite the high spatial and temporal variability of tropospheric ozone, there are limited observations of past ozone changes at the global scale (Dragani, 2011; Ebojie et al., 2016; Gaudel et al., 2018; Young et al., 2018). Hence, Earth system models remain valuable tools to understand the evolution of tropospheric ozone and the interactions between tropospheric ozone and regional climate (Archibald et al., 2020; Collins et al., 2017; Young et al., 2018). Datasets from Coupled Modeling Intercomparison Project Phase 6 (CMIP6) models provide an important source to better identify the effects of ENSO on global tropospheric ozone.

In the present study, we evaluated the causal impacts of ENSO on tropospheric ozone at the global scale using data from the historical simulations of CMIP6 models. We also discussed the coherency across CMIP6 models in reproducing the connection between ENSO and tropospheric ozone.

2 Materials and Methods

2.1 Datasets

We used monthly data of mole fraction of ozone in air (i.e., variable 'o3') at different air pressure levels (i.e., 1000, 850, 500, and 300 hPa). The CMIP6 models with ozone data available for the historical simulations (Eyring et al., 2016) over the 1850-2014 period are listed in Table S1. The use of various model outputs reduces the uncertainty of the connections between ENSO and tropospheric ozone.

There are biases in simulating tropospheric ozone variations in the models (Griffiths et al., 2021; Turnock et al., 2020; Young et al., 2018), however, CMIP model outputs are still helpful to investigate the effects of ENSO on tropospheric ozone (Archibald et al., 2020; Young et al., 2018).

We employed monthly sea level pressure (SLP) and sea surface temperature (SST) to calculate the time series of the major climate modes (see also section Text S1).

2.2 Methods

We assess the possibility of the impacts of ENSO on tropospheric ozone based on the approach employed in recent studies (Le and Bae, 2020, 2022). This method was established using a multivariate predictive model to assess the probability for the

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absence of Granger causal effects of ENSO on ozone concentrations. In the computations, we considered the confounding impacts of other major climate modes (i.e., the dipole mode index (DMI; Saji et al., 1999), the Southern Annular Mode (SAM; e.g., Cai et al., 2011), and the North Atlantic Oscillation (NAO; e.g., Hurrell et al., 2003)). Given that the climate changes in the Indian and Atlantic oceans can affect the tropical Pacific (Cai et al., 2019; Ha et al., 2017; Le et al., 2020; Le and Bae, 2019), and modify the connections between ENSO and ozone concentrations, these analyses provide a realistic estimate for the response of ozone concentrations to ENSO. Additional information of the methods employed in this study is described in section Text S1.

3 Results

Figure 1 depicts the models' mean map of ozone concentrations at different air pressure levels for the period 1850-2014 of the CMIP6 historical simulations. In the middle and lower troposphere, ozone is higher in the northern hemisphere compared to the southern hemisphere (Figure 1). The agreement between models fluctuates at different air pressure levels. For example, in the upper troposphere (i.e., at 300 hPa pressure level), high consistency across the model is found in the mid-latitude regions, while this consistency is lower in the tropics and polar regions (Figure 1a). In the middle troposphere (i.e., at 500 hPa pressure level), the models' agreement is mainly found in the northern hemisphere (Figure 1b). The simulations of near-surface ozone (i.e., at 850 hPa) are consistent over the tropics and parts of the northern hemisphere (Figure 1c), while the models' agreement is low in reproducing surface ozone (i.e., at 1000 hPa) for most regions (Figure 1d). The standard deviation is normally higher in the tropics compared to other regions (Figure S1).

Figure 2 displays the causal effects of ENSO on global ozone concentrations for the historical period 1850-2014. In Figure 2, we show that the response of ozone to ENSO may vary depending on specific air pressure level. For instance, ENSO impacts on ozone in the upper troposphere (i.e., at 300 hPa pressure level) can be observed over parts of the Pacific Ocean and North America (Figure 2a). In these areas, ENSO is unlikely to exhibit no causal influences on ozone concentrations (i.e., *p*-values were lower than 0.33). The response of ozone to ENSO in the middle troposphere (i.e., at 500 hPa pressure level) is very limited over the tropical Pacific and Atlantic Oceans (Figure 2b). We observe more significant impacts of ENSO on ozone in the lower troposphere compared to the upper and middle troposphere. Specifically, tropical ozone concentrations at near surface (i.e., at 850 hPa) and surface (i.e., at 1000 hPa) levels appear to be sensitive to ENSO (Figures 2c and d). In addition, ENSO impacts on surface ozone can be found over part of the northern North Pacific and mid-latitude regions in the southern hemisphere (Figure 2d). We observe causal influences of ENSO on ozone over Antarctica, however, these influences show low agreement between models (Figures 2c and d). While the signature of ENSO on ozone variations is generally weak over continents of the lower and middle troposphere (Figures 2b-d), this signature is, however, stronger in the upper troposphere over North America (Figure 2a). These results imply that the effects of ENSO on tropospheric ozone over lands are nonsignificant for most regions.

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Differences between CMIP6 models in replicating the influences of ENSO on surface (1000 hPa) ozone are shown in Figure 3. Similar results for other pressure levels (300, 500, and 850 hPa) are presented in Figures S2-S4. As revealed in Figure 3, several models (i.e., BCC_CSM2_MR, IPSL_CM6A_LR, and MPI_ESM1_2_LR) may not reproduce the significant influences of ENSO on surface ozone over the tropical Pacific and Indian Oceans as described in Figure 2d. The models IPSL_CM6A_LR and MPI_ESM1_2_LR may underestimate the response of surface ozone to ENSO over the mid-latitude regions in the southern hemisphere compared to other models. The agreement between models for the impacts of ENSO on surface ozone is low over continents (Figure 2d), partly due to the discrepancy in simulating ozone variability (Figure 1d). While there are biases in simulating the response of surface ozone to ENSO (Figure 2d), these responses in the middle and upper troposphere appear to be more consistent across models (Figures 2a-c, S2-4).

Springtime surface ozone is more sensitive to ENSO compared to other seasons (Figure 4). In particular, the clear response of springtime surface ozone over the high-latitude north Pacific can be observed (Figure 4a). The impacts of ENSO on surface ozone of other seasons are limited (e.g., over the tropical Pacific and part of southern North America, Figure 4b-d). The results for other air pressure levels (300, 500, and 850 hPa) are shown in Figures S5-S7. We note that the response of springtime ozone at higher pressure levels is weaker compared to springtime surface ozone for most regions, except for the upper troposphere over east Asia and northwestern North America (Figure S5a). Consistent with the results illustrated in Figure 2b, the impacts of ENSO on seasonal ozone in the middle troposphere (500 hPa) are largely nonsignificant for all seasons (Figure S6).

4 Discussion and conclusions

The effects of ENSO on tropospheric ozone over the tropical Pacific (Figures 2-4) show agreement with previous works (Chandra et al., 2007; Peiro et al., 2018). ENSO causes changes in the tropospheric ozone budget over the tropical Pacific by modulating the Walker circulation (Chandra et al., 2007), wind systems (Cai et al., 2021; Le and Bae, 2020; Yeh et al., 2018), and inducing biomass burning (Chandra et al., 2009; Le et al., 2022). Further, significant ENSO impacts on tropical ocean regions described in Figures 2-4 are in agreement with recent works (Olsen et al., 2016; Wespes et al., 2017) using satellite data.

The significant impacts of ENSO on ozone in the upper troposphere (300 hPa) over the southern and western North America (Figures 2a and S5a) might be associated with the transport of ozone from east Asia (Cooper et al., 2010; Doherty, 2015; Lin et al., 2015). However, these impacts cannot reach the surface levels (Figures 2c-d, S6a, and S7a), consistent with recent work (Lin et al., 2015).

We note that the models without the Atmospheric Chemistry module (BCC_CSM2_MR, IPSL_CM6A_LR, MPI_ESM1_2_LR; See Table S1) provide different results of ENSO impacts compared to the rest models (Figures 3). Hence, improvement of the Atmospheric Chemistry module in the models may provide further understanding of the connection between ENSO and ozone variations.

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The weak impacts of ENSO on the mid-level tropospheric ozone (i.e., 500 hPa level, described in Figures 2a and 3) might be due to the strong exchange between stratospheric ozone and middle to upper tropospheric ozone (Liu et al., 2017; Meul et al., 2018; Neu et al., 2014; Williams et al., 2019).

Several models showed ENSO effects on tropospheric ozone over Antarctica with a low agreement between models (Figures 2-4). These impacts might be associated with the signature of ENSO on stratospheric ozone anomalies over Antarctica (Li et al., 2021; Lin and Qian, 2019).

Given that the tropospheric ozone burden and the ozone-induced impacts may increase in some regions in the future (Doherty et al., 2013; Franz and Zaehle, 2021; Gaudel et al., 2020; Griffiths et al., 2021; Verstraeten et al., 2015; Zanis et al., 2022), further analyses of ENSO impacts on tropospheric ozone in future climate projections are necessary.

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Data Availability

The data that support the findings of this study are openly available at the following website: https://esgf-node.llnl.gov/search/cmip6/.

Author contribution

TL designed the study, performed the data analysis, and wrote the manuscript. SHK, JYH and DHB contributed to the interpretation of results and the writing of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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References

Archibald, A. T., Neu, J. L., Elshorbany, Y. F., Cooper, O. R., Young, P. J., Akiyoshi, H., Cox, R. A., Coyle, M., Derwent, R. G., Deushi, M., Finco, A., Frost, G. J., Galbally, I. E., Gerosa, G., Granier, C., Griffiths, P. T., Hossaini, R., Hu, L., Jöckel, P., Josse, B., Lin, M. Y., Mertens, M., Morgenstern, O., Naja, M., Naik, V., Oltmans, S., Plummer, D. A., Revell, L. E., Saiz-Lopez, A., Saxena, P., Shin, Y. M., Shahid, I., Shallcross, D., Tilmes, S., Trickl, T., Wallington, T. J., Wang, T., Worden, H. M. and Zeng, G.: Tropospheric Ozone Assessment Report, Elem. Sci. Anthr., 8(1), 1–53, doi:10.1525/elementa.2020.034, 2020.

Bjerknes, J.: Atmospheric teleconnections from the equatorial Pacific, Mon. Weather Rev., 97(3), 163–172, doi:10.1175/1520-0493(1969)097<0163:ATFTEP>2.3.CO;2, 1969.

Cai, W., Sullivan, A. and Cowan, T.: Interactions of ENSO, the IOD, and the SAM in CMIP3 Models, J. Clim., 24(6), 1688–1704, doi:10.1175/2010JCLI3744.1, 2011.

Cai, W., Wu, L., Lengaigne, M., Li, T., McGregor, S., Kug, J.-S., Yu, J.-Y., Stuecker, M. F., Santoso, A., Li, X., Ham, Y.-G., Chikamoto, Y., Ng, B., McPhaden, M. J., Du, Y., Dommenget, D., Jia, F., Kajtar, J. B., Keenlyside, N., Lin, X., Luo, J.-J., Martín-Rey, M., Ruprich-Robert, Y., Wang, G., Xie, S.-P., Yang, Y., Kang, S. M., Choi, J.-Y., Gan, B., Kim, G.-I., Kim, C.-E., Kim, S., Kim, J.-H. and Chang, P.: Pantropical climate interactions, Science (80-.)., 363(6430), eaav4236, doi:10.1126/science.aav4236, 2019.

Cai, W., McPhaden, M. J., Grimm, A. M., Rodrigues, R. R., Taschetto, A. S., Garreaud, R. D., Dewitte, B., Poveda, G., Ham, Y.-G., Santoso, A., Ng, B., Anderson, W., Wang, G., Geng, T., Jo, H.-S., Marengo, J. A., Alves, L. M., Osman, M., Li, S., Wu, L., Karamperidou, C., Takahashi, K. and Vera, C.: Climate impacts of the El Niño–Southern Oscillation on South America, Nat. Rev. Earth Environ., 1(4), 215–231, doi:10.1038/s43017-020-0040-3, 2020.

Cai, W., Santoso, A., Collins, M., Dewitte, B., Karamperidou, C., Kug, J.-S., Lengaigne, M., McPhaden, M. J., Stuecker, M. F., Taschetto, A. S., Timmermann, A., Wu, L., Yeh, S.-W., Wang, G., Ng, B., Jia, F., Yang, Y., Ying, J., Zheng, X.-T., Bayr, T., Brown, J. R., Capotondi, A., Cobb, K. M., Gan, B., Geng, T., Ham, Y.-G., Jin, F.-F., Jo, H.-S., Li, X., Lin, X., McGregor, S., Park, J.-H., Stein, K., Yang, K., Zhang, L. and Zhong, W.: Changing El Niño–Southern Oscillation in a warming climate, Nat. Rev. Earth Environ., 2(9), 628–644, doi:10.1038/s43017-021-00199-z, 2021.

Chandra, S., Ziemke, J. R., Schoeberl, M. R., Froidevaux, L., Read, W. G., Levelt, P. F. and Bhartia, P. K.: Effects of the 2004 El Niño on tropospheric ozone and water vapor, Geophys. Res. Lett., 34(6), L06802, doi:10.1029/2006GL028779, 2007.

Chandra, S., Ziemke, J. R., Duncan, B. N., Diehl, T. L., Livesey, N. J. and Froidevaux, L.: Effects of the 2006 El Niño on tropospheric ozone and carbon monoxide: implications for dynamics and biomass burning, Atmos. Chem. Phys., 9(13), 4239–4249, doi:10.5194/acp-9-4239-2009, 2009.

Collins, W. J., Lamarque, J.-F., Schulz, M., Boucher, O., Eyring, V., Hegglin, M. I., Maycock, A., Myhre, G., Prather, M., Shindell, D. and Smith, S. J.: AerChemMIP: quantifying the effects of chemistry and aerosols in CMIP6, Geosci. Model Dev., 10(2), 585–607, doi:10.5194/gmd-10-585-2017, 2017.

Cooper, O. R., Parrish, D. D., Stohl, A., Trainer, M., Nédélec, P., Thouret, V., Cammas, J. P., Oltmans, S. J., Johnson, B. J., Tarasick, D., Leblanc, T., McDermid, I. S., Jaffe, D., Gao, R., Stith, J., Ryerson, T., Aikin, K., Campos, T., Weinheimer, A. and Avery, M. A.: Increasing springtime ozone mixing ratios in the free troposphere over western North America, Nature, 463(7279), 344–348, doi:10.1038/nature08708, 2010.

Daskalakis, N., Gallardo, L., Kanakidou, M., Nüß, J. R., Menares, C., Rondanelli, R., Thompson, A. M. and Vrekoussis, M.: Impact of biomass burning and stratospheric intrusions in the remote South Pacific Ocean troposphere, Atmos. Chem. Phys., 22(6), 4075–4099, doi:10.5194/acp-22-4075-2022, 2022.

Doherty, R. M.: Ozone pollution from near and far, Nat. Geosci., 8(9), 664–665, doi:10.1038/ngeo2497, 2015.

Doherty, R. M., Stevenson, D. S., Johnson, C. E., Collins, W. J. and Sanderson, M. G.: Tropospheric ozone and El Niño–Southern Oscillation: Influence of atmospheric dynamics, biomass burning emissions, and future climate change, J. Geophys. Res., 111(D19), D19304, doi:10.1029/2005JD006849, 2006.

Doherty, R. M., Wild, O., Shindell, D. T., Zeng, G., MacKenzie, I. A., Collins, W. J., Fiore, A. M., Stevenson, D. S., Dentener, F. J., Schultz, M. G., Hess, P., Derwent, R. G. and Keating, T. J.: Impacts of climate change on surface ozone and intercontinental ozone pollution: A multi-model study, J. Geophys. Res. Atmos., 118(9), 3744–3763, doi:10.1002/jgrd.50266, 2013.

Domeisen, D. I. V., Garfinkel, C. I. and Butler, A. H.: The Teleconnection of El Niño Southern Oscillation to the Stratosphere, Rev. Geophys., 57(1), 5–47, doi:10.1029/2018RG000596, 2019.

Dragani, R.: On the quality of the ERA-Interim ozone reanalyses: comparisons with satellite data, Q. J. R. Meteorol. Soc., 137(658), 1312–1326, doi:10.1002/qj.821, 2011.

Ebojie, F., Burrows, J. P., Gebhardt, C., Ladstätter-Weißenmayer, A., von Savigny, C., Rozanov, A., Weber, M. and Bovensmann, H.: Global tropospheric ozone variations from 2003 to 2011 as seen by SCIAMACHY, Atmos. Chem. Phys., 16(2), 417–436, doi:10.5194/acp-16-417-2016, 2016.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J. and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geosci. Model Dev., 9(5), 1937–1958, doi:10.5194/gmd-9-1937-2016, 2016.

Fleming, Z. L., Doherty, R. M., Von Schneidemesser, E., Malley, C. S., Cooper, O. R., Pinto, J. P., Colette, A., Xu, X., Simpson, D., Schultz, M. G., Lefohn, A. S., Hamad, S., Moolla, R., Solberg, S. and Feng, Z.: Tropospheric Ozone Assessment Report: Present-day ozone distribution and trends relevant to human health, Elementa, 6, doi:10.1525/elementa.273, 2018.

Franz, M. and Zaehle, S.: Competing effects of nitrogen deposition and ozone exposure on northern hemispheric terrestrial carbon uptake and storage, 1850-2099, Biogeosciences, 18(10), 3219–3241, doi:10.5194/bg-18-3219-2021, 2021.

Franz, M., Alonso, R., Arneth, A., Büker, P., Elvira, S., Gerosa, G., Emberson, L., Feng, Z., Le Thiec, D., Marzuoli, R., Oksanen, E., Uddling, J., Wilkinson, M. and Zaehle, S.: Evaluation of simulated ozone effects in forest ecosystems against biomass damage estimates from fumigation experiments, Biogeosciences, 15(22), 6941–6957, doi:10.5194/bg-15-6941-2018, 2018.

Ganzeveld, L., Helmig, D., Fairall, C. W., Hare, J. and Pozzer, A.: Atmosphere-ocean ozone exchange: A global modeling study of biogeochemical, atmospheric, and waterside turbulence dependencies, Global Biogeochem. Cycles, 23(4), n/a-n/a, doi:10.1029/2008GB003301, 2009.

Gaudel, A., Cooper, O. R., Ancellet, G., Barret, B., Boynard, A., Burrows, J. P., Clerbaux, C., Coheur, P.-F., Cuesta, J., Cuevas, E., Doniki, S., Dufour, G., Ebojie, F., Foret, G., Garcia, O., Granados-Muñoz, M. J., Hannigan, J. W., Hase, F., Hassler, B., Huang, G., Hurtmans, D., Jaffe, D., Jones, N., Kalabokas, P., Kerridge, B., Kulawik, S., Latter, B., Leblanc, T., Le Flochmoën, E., Lin, W., Liu, J., Liu, X., Mahieu, E., McClure-Begley, A., Neu, J. L., Osman, M., Palm, M., Petetin, H., Petropavlovskikh, I., Querel, R., Rahpoe, N., Rozanov, A., Schultz, M. G., Schwab, J., Siddans, R., Smale, D., Steinbacher, M., Tanimoto, H., Tarasick, D. W., Thouret, V., Thompson, A. M., Trickl, T., Weatherhead, E., Wespes, C., Worden, H. M., Vigouroux, C., Xu, X., Zeng, G. and Ziemke, J.: Tropospheric Ozone Assessment Report: Present-day distribution and trends of tropospheric ozone relevant to climate and global atmospheric chemistry model evaluation, edited by D. Helmig and A. Lewis, Elem. Sci. Anthr., 6, doi:10.1525/elementa.291, 2018.

Gaudel, A., Cooper, O. R., Chang, K.-L., Bourgeois, I., Ziemke, J. R., Strode, S. A., Oman, L. D., Sellitto, P., Nédélec, P., Blot, R., Thouret, V. and Granier, C.: Aircraft observations since the 1990s reveal increases of tropospheric ozone at multiple locations across the Northern Hemisphere, Sci. Adv., 6(34), 1–12, doi:10.1126/sciadv.aba8272, 2020.

Gauss, M., Myhre, G., Isaksen, I. S. A., Grewe, V., Pitari, G., Wild, O., Collins, W. J., Dentener, F. J., Ellingsen, K., Gohar, L. K., Hauglustaine, D. A., Iachetti, D., Lamarque, F., Mancini, E., Mickley, L. J., Prather, M. J., Pyle, J. A., Sanderson, M. G., Shine, K. P., Stevenson, D. S., Sudo, K., Szopa, S. and Zeng, G.: Radiative forcing since preindustrial times due to ozone change in the troposphere and the lower stratosphere, Atmos. Chem. Phys., 6(3), 575–599, doi:10.5194/acp-6-575-2006, 2006.

Griffiths, P. T., Murray, L. T., Zeng, G., Shin, Y. M., Abraham, N. L., Archibald, A. T., Deushi, M., Emmons, L. K., Galbally, I. E., Hassler, B., Horowitz, L. W., Keeble, J., Liu, J., Moeini, O., Naik, V., O'Connor, F. M., Oshima, N., Tarasick, D., Tilmes, S., Turnock, S. T., Wild, O., Young, P. J. and Zanis, P.: Tropospheric ozone in CMIP6 simulations, Atmos. Chem. Phys., 21(5), 4187–4218, doi:10.5194/acp-21-4187-2021, 2021.

Ha, K.-J., Chu, J.-E., Lee, J.-Y. and Yun, K.-S.: Interbasin coupling between the tropical Indian and Pacific Ocean on interannual timescale: observation and CMIP5 reproduction, Clim. Dyn., 48(1–2), 459–475, doi:10.1007/s00382-016-3087-6, 2017.

Hurrell, J. W., Kushnir, Y., Ottersen, G. and Visbeck, M.: An overview of the North Atlantic Oscillation, in Geophysical Monograph American Geophysical Union, pp. 1–35, American Geophysical Union., 2003.

Jiang, Z. and Li, J.: Impact of eastern and central Pacific El Niño on lower tropospheric ozone in China, Atmos. Chem. Phys., 22(11), 7273–7285, doi:10.5194/acp-22-7273-2022, 2022.

Koumoutsaris, S., Bey, I., Generoso, S. and Thouret, V.: Influence of El Niño–Southern Oscillation on the interannual variability of tropospheric ozone in the northern midlatitudes, J. Geophys. Res., 113(D19), D19301, doi:10.1029/2007JD009753, 2008.

Le, T. and Bae, D.-H.: Response of global evaporation to major climate modes in historical and future Coupled Model Intercomparison Project Phase 5 simulations, Hydrol. Earth Syst. Sci., 24(3), 1131–1143, doi:10.5194/hess-24-1131-2020, 2020.

Le, T. and Bae, D.-H. H.: Causal Links on Interannual Timescale Between ENSO and the IOD in CMIP5 Future Simulations, Geophys. Res. Lett., 46(5), 2820–2828, doi:10.1029/2018GL081633, 2019.

Le, T. and Bae, D.: Causal Impacts of El Niño–Southern Oscillation on Global Soil Moisture Over the Period 2015–2100, Earth's Futur., 10(3), doi:10.1029/2021EF002522, 2022.

Le, T., Ha, K.-J. J., Bae, D.-H. H. and Kim, S.-H. H.: Causal effects of Indian Ocean Dipole on El Niño-Southern Oscillation during 1950-2014 based on high-resolution models and reanalysis data, Environ. Res. Lett., 15(10), 1040b6, doi:10.1088/1748-9326/abb96d, 2020.

Le, T., Kim, S. and Bae, D.: Decreasing causal impacts of El Niño–Southern Oscillation on future fire activities, Sci. Total Environ., 826, 154031, doi:10.1016/j.scitotenv.2022.154031, 2022.

Li, X., Cai, W., Meehl, G. A., Chen, D., Yuan, X., Raphael, M., Holland, D. M., Ding, Q., Fogt, R. L., Markle, B. R., Wang, G., Bromwich, D. H., Turner, J., Xie, S. P., Steig, E. J., Gille, S. T., Xiao, C., Wu, B., Lazzara, M. A., Chen, X., Stammerjohn, S., Holland, P. R., Holland, M. M., Cheng, X., Price, S. F., Wang, Z., Bitz, C. M., Shi, J., Gerber, E. P., Liang, X., Goosse, H., Yoo, C., Ding, M., Geng, L., Xin, M., Li, C., Dou, T., Liu, C., Sun, W., Wang, X. and Song, C.: Tropical teleconnection impacts on Antarctic climate changes, Nat. Rev. Earth Environ., 2(10), 680–698, doi:10.1038/s43017-021-00204-5, 2021.

https://doi.org/10.5194/egusphere-2023-207
Preprint. Discussion started: 26 June 2023

Lin, J. and Qian, T.: Impacts of the ENSO Lifecycle on Stratospheric Ozone and Temperature, Geophys. Res. Lett., 46(17–18), 10646–10658, doi:10.1029/2019GL083697, 2019.

Lin, M., Fiore, A. M., Horowitz, L. W., Langford, A. O., Oltmans, S. J., Tarasick, D. and Rieder, H. E.: Climate variability modulates western US ozone air quality in spring via deep stratospheric intrusions, Nat. Commun., 6(May), 1–11, doi:10.1038/ncomms8105, 2015.

Lin, M., Malyshev, S., Shevliakova, E., Paulot, F., Horowitz, L. W., Fares, S., Mikkelsen, T. N. and Zhang, L.: Sensitivity of Ozone Dry Deposition to Ecosystem-Atmosphere Interactions: A Critical Appraisal of Observations and Simulations, Global Biogeochem. Cycles, 33(10), 1264–1288, doi:10.1029/2018GB006157, 2019.

Liu, J., Rodriguez, J. M., Steenrod, S. D., Douglass, A. R., Logan, J. A., Olsen, M. A., Wargan, K. and Ziemke, J. R.: Causes of interannual variability over the southern hemispheric tropospheric ozone maximum, Atmos. Chem. Phys., 17(5), 3279–3299, doi:10.5194/acp-17-3279-2017, 2017.

Lu, X., Zhang, L. and Shen, L.: Meteorology and Climate Influences on Tropospheric Ozone: a Review of Natural Sources, Chemistry, and Transport Patterns, Curr. Pollut. Reports, 5(4), 238–260, doi:10.1007/s40726-019-00118-3, 2019.

McPhaden, M. J., Zebiak, S. E. and Glantz, M. H.: ENSO as an integrating concept in earth science., Science, 314(December), 1740–1745, doi:10.1126/science.1132588, 2006.

Meul, S., Langematz, U., Kröger, P., Oberländer-Hayn, S. and Jöckel, P.: Future changes in the stratosphere-to-troposphere ozone mass flux and the contribution from climate change and ozone recovery, Atmos. Chem. Phys., 18(10), 7721–7738, doi:10.5194/acp-18-7721-2018, 2018.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T. and Zhan, H.: Anthropogenic and Natural Radiative Forcing: In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change., 2013.

Neu, J. L., Flury, T., Manney, G. L., Santee, M. L., Livesey, N. J. and Worden, J.: Tropospheric ozone variations governed by changes in stratospheric circulation, Nat. Geosci., 7(5), 340–344, doi:10.1038/ngeo2138, 2014.

Oliver, R. J., Mercado, L. M., Sitch, S., Simpson, D., Medlyn, B. E., Lin, Y. S. and Folberth, G. A.: Large but decreasing effect of ozone on the European carbon sink, Biogeosciences, 15(13), 4245–4269, doi:10.5194/bg-15-4245-2018, 2018.

Olsen, M. A., Wargan, K. and Pawson, S.: Tropospheric column ozone response to ENSO in GEOS-5 assimilation of OMI and MLS ozone data, Atmos. Chem. Phys., 16(11), 7091–7103, doi:10.5194/acp-16-7091-2016, 2016.

Olsen, M. A., Manney, G. L. and Liu, J.: The ENSO and QBO Impact on Ozone Variability and Stratosphere-Troposphere Exchange Relative to the Subtropical Jets, J. Geophys. Res. Atmos., 124(13), 7379–7392, doi:10.1029/2019JD030435, 2019.

Oman, L. D., Ziemke, J. R., Douglass, A. R., Waugh, D. W., Lang, C., Rodriguez, J. M. and Nielsen, J. E.: The response of tropical tropospheric ozone to ENSO, Geophys. Res. Lett., 38(13), n/a-n/a, doi:10.1029/2011GL047865, 2011.

Oman, L. D., Douglass, A. R., Ziemke, J. R., Rodriguez, J. M., Waugh, D. W. and Nielsen, J. E.: The ozone response to ENSO in Aura satellite measurements and a chemistry-climate simulation, J. Geophys. Res. Atmos., 118(2), 965–976, doi:10.1029/2012JD018546, 2013.

Peiro, H., Emili, E., Cariolle, D., Barret, B. and Le Flochmoën, E.: Multi-year assimilation of IASI and MLS ozone retrievals: variability of tropospheric ozone over the tropics in response to ENSO, Atmos. Chem. Phys., 18(9), 6939–6958, doi:10.5194/acp-18-6939-2018, 2018.

Peron, A., Kaser, L., Charlott Fitzky, A., Graus, M., Halbwirth, H., Greiner, J., Wohlfahrt, G., Rewald, B., Sandén, H. and Karl, T.: Combined effects of ozone and drought stress on the emission of biogenic volatile organic compounds from Quercus robur L., Biogeosciences, 18(2), 535–556, doi:10.5194/bg-18-535-2021, 2021.

https://doi.org/10.5194/egusphere-2023-207
Preprint. Discussion started: 26 June 2023

Roberts, H. R., Dodd, I. C., Hayes, F. and Ashworth, K.: Chronic tropospheric ozone exposure reduces seed yield and quality in spring and winter oilseed rape, Agric. For. Meteorol., 316(August 2021), 108859, doi:10.1016/j.agrformet.2022.108859, 2022.

Rowlinson, M. J., Rap, A., Arnold, S. R., Pope, R. J., Chipperfield, M. P., McNorton, J., Forster, P., Gordon, H., Pringle, K. J., Feng, W., Kerridge, B. J., Latter, B. L. and Siddans, R.: Impact of El Niño–Southern Oscillation on the interannual variability of methane and tropospheric ozone, Atmos. Chem. Phys., 19(13), 8669–8686, doi:10.5194/acp-19-8669-2019, 2019.

Saji, N. H., Goswami, B. N., Vinayachandran, P. N. and Yamagata, T.: A dipole mode in the tropical Indian Ocean, Nature, 401(6751), 360–363, doi:10.1038/43854, 1999.

Schauberger, B., Rolinski, S., Schaphoff, S. and Müller, C.: Global historical soybean and wheat yield loss estimates from ozone pollution considering water and temperature as modifying effects, Agric. For. Meteorol., 265(October 2018), 1–15, doi:10.1016/j.agrformet.2018.11.004, 2019.

Turnock, S. T., Allen, R. J., Andrews, M., Bauer, S. E., Deushi, M., Emmons, L., Good, P., Horowitz, L., John, J. G., Michou, M., Nabat, P., Naik, V., Neubauer, D., O'Connor, F. M., Olivié, D., Oshima, N., Schulz, M., Sellar, A., Shim, S., Takemura, T., Tilmes, S., Tsigaridis, K., Wu, T. and Zhang, J.: Historical and future changes in air pollutants from CMIP6 models, Atmos. Chem. Phys., 20(23), 14547–14579, doi:10.5194/acp-20-14547-2020, 2020.

Verstraeten, W. W., Neu, J. L., Williams, J. E., Bowman, K. W., Worden, J. R. and Boersma, K. F.: Rapid increases in tropospheric ozone production and export from China, Nat. Geosci., 8(9), 690–695, doi:10.1038/ngeo2493, 2015.

Wang, T., Xue, L., Feng, Z., Dai, J., Zhang, Y. and Tan, Y.: Ground-level ozone pollution in China: a synthesis of recent findings on influencing factors and impacts, Environ. Res. Lett., 17(6), 063003, doi:10.1088/1748-9326/ac69fe, 2022.

Wespes, C., Hurtmans, D., Clerbaux, C. and Coheur, P. -F.: O 3 variability in the troposphere as observed by IASI over 2008–2016: Contribution of atmospheric chemistry and dynamics, J. Geophys. Res. Atmos., 122(4), 2429–2451, doi:10.1002/2016JD025875, 2017.

Wie, J., Moon, B.-K., Yeh, S.-W., Park, R. J. and Kim, B.-G.: La Niña-related tropospheric column ozone enhancement over East Asia, Atmos. Environ., 261(October 2020), 118575, doi:10.1016/j.atmosenv.2021.118575, 2021.

Williams, R. S., Hegglin, M. I., Kerridge, B. J., Jöckel, P., Latter, B. G. and Plummer, D. A.: Characterising the seasonal and geographical variability in tropospheric ozone, stratospheric influence and recent changes, Atmos. Chem. Phys., 19(6), 3589–3620, doi:10.5194/acp-19-3589-2019, 2019.

Xu, L., Yu, J.-Y., Schnell, J. L. and Prather, M. J.: The seasonality and geographic dependence of ENSO impacts on U.S. surface ozone variability, Geophys. Res. Lett., 44(7), 3420–3428, doi:10.1002/2017GL073044, 2017.

Yang, Y., Li, M., Wang, H., Li, H., Wang, P., Li, K., Gao, M. and Liao, H.: ENSO modulation of summertime tropospheric ozone over China, Environ. Res. Lett., 17(3), 034020, doi:10.1088/1748-9326/ac54cd, 2022.

Yeh, S.-W., Cai, W., Min, S.-K., McPhaden, M. J., Dommenget, D., Dewitte, B., Collins, M., Ashok, K., An, S.-I., Yim, B.-Y. and Kug, J.-S.: ENSO Atmospheric Teleconnections and Their Response to Greenhouse Gas Forcing, Rev. Geophys., 56(1), 185–206, doi:10.1002/2017RG000568, 2018.

Young, P. J., Naik, V., Fiore, A. M., Gaudel, A., Guo, J., Lin, M. Y., Neu, J. L., Parrish, D. D., Rieder, H. E., Schnell, J. L., Tilmes, S., Wild, O., Zhang, L., Ziemke, J., Brandt, J., Delcloo, A., Doherty, R. M., Geels, C., Hegglin, M. I., Hu, L., Im, U., Kumar, R., Luhar, A., Murray, L., Plummer, D., Rodriguez, J., Saiz-Lopez, A., Schultz, M. G., Woodhouse, M. T. and Zeng, G.: Tropospheric Ozone Assessment Report: Assessment of global-scale model performance for global and regional ozone distributions, variability, and trends, edited by D. Helmig and A. Lewis, Elem. Sci. Anthr., 6, doi:10.1525/elementa.265, 2018.

Zanis, P., Akritidis, D., Turnock, S., Naik, V., Szopa, S., Georgoulias, A. K., Bauer, S. E., Deushi, M., Horowitz, L. W., Keeble, J., Le Sager, P., O'Connor, F. M., Oshima, N., Tsigaridis, K. and van Noije, T.: Climate change penalty and benefit on surface ozone: a global perspective based on CMIP6 earth system models, Environ. Res. Lett., 17(2), 024014, doi:10.1088/1748-9326/ac4a34, 2022.

Zeng, G. and Pyle, J. A.: Influence of El Niño Southern Oscillation on stratosphere/troposphere exchange and the global tropospheric ozone budget, Geophys. Res. Lett., 32(1), L01814, doi:10.1029/2004GL021353, 2005.

Zhang, J., Tian, W., Xie, F., Li, Y., Wang, F., Huang, J. and Tian, H.: Influence of the El Niño southern oscillation on the total ozone column and clear-sky ultraviolet radiation over China, Atmos. Environ., 120, 205–216, doi:10.1016/j.atmosenv.2015.08.080, 2015.

Ziemke, J. R., Douglass, A. R., Oman, L. D., Strahan, S. E. and Duncan, B. N.: Tropospheric ozone variability in the tropics from ENSO to MJO and shorter timescales, Atmos. Chem. Phys., 15(14), 8037–8049, doi:10.5194/acp-15-8037-2015, 2015.

https://doi.org/10.5194/egusphere-2023-207
Preprint. Discussion started: 26 June 2023

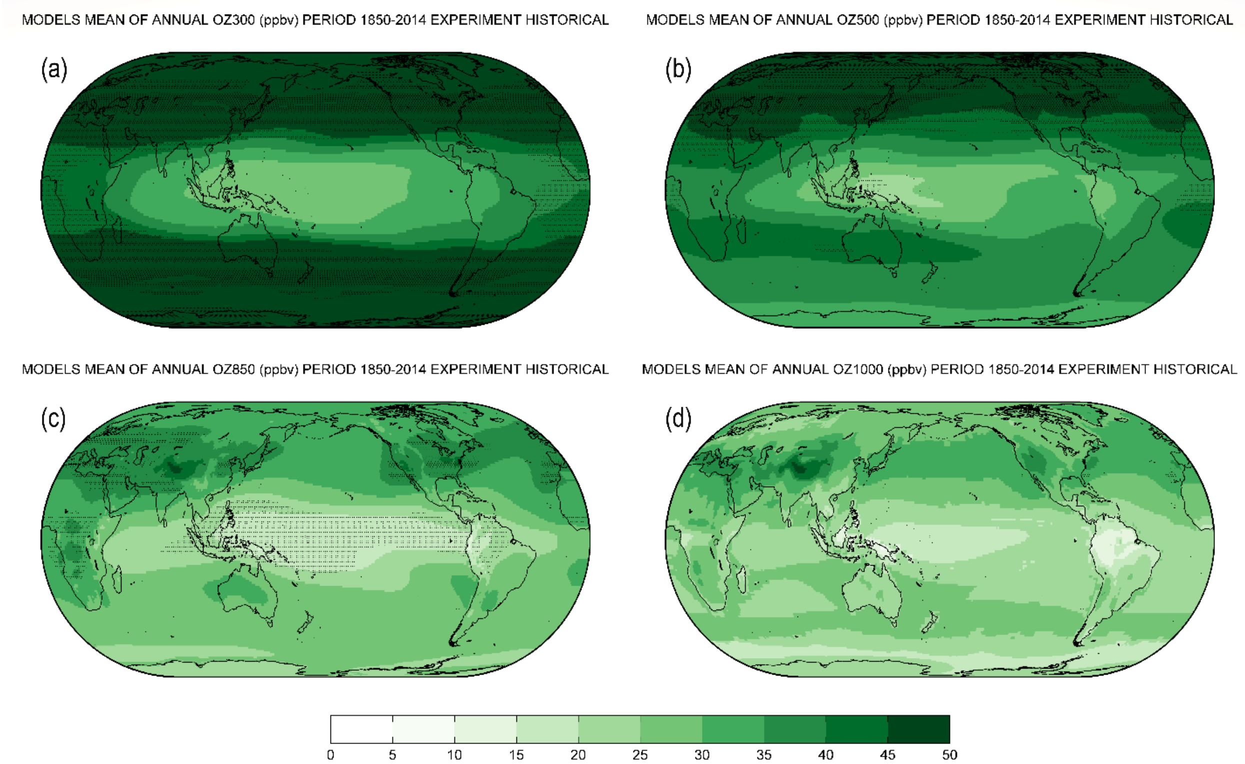

Figure 1. Multi-model mean map of annual mean ozone concentrations (ppbv) for the historical experiment over the 1850-2014 period at 300 hPa (a), 500 hPa (b), 850 hPa (c) and 1000 hPa (d) pressure levels, respectively. Stippling indicates that at least 70% of total models show agreement on the mean ozone concentrations of all models at given grid point. The agreement of an individual model is identified when the difference between the selected model's ozone concentrations and the multi-model mean ozone concentrations is less than one standard deviation of the multi-model mean ozone concentrations.

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Preprint. Discussion started: 26 June 2023

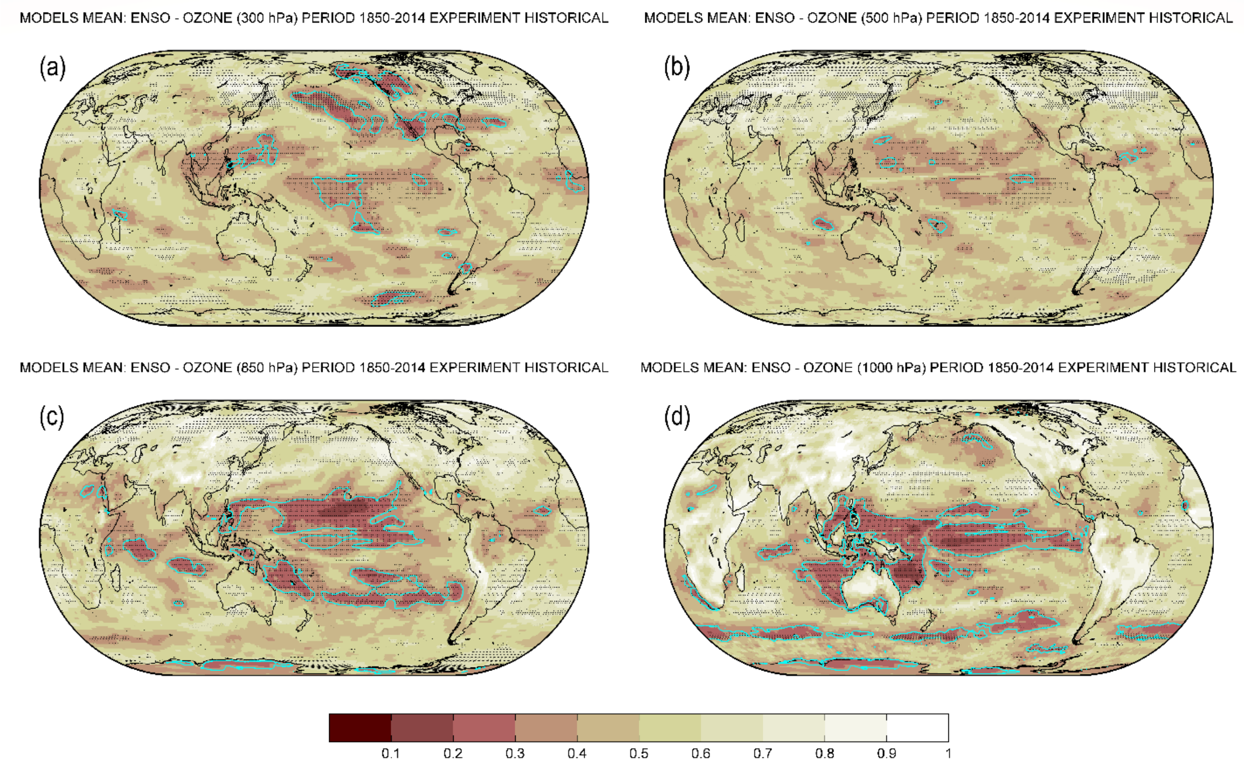

Figure 2. Map of multi-model mean probability for the absence of Granger causality from ENSO to annual ozone concentrations for the historical experiment over the 1850-2014 period at 300 hPa (a), 500 hPa (b), 850 hPa (c) and 1000 hPa (d) pressure levels, respectively. Stippling indicates that at least 70% of total models show agreement on the mean probability of all models at given grid point. The agreement of an individual model is identified when the difference between the selected model's probability and the multi-model mean probability is less than one standard deviation of the multi-model mean probability. The cyan contour line denotes *p*-value = 0.33. Brown shades indicate low probability of no Granger causality. ENSO = El Niño–Southern Oscillation.

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Preprint. Discussion started: 26 June 2023

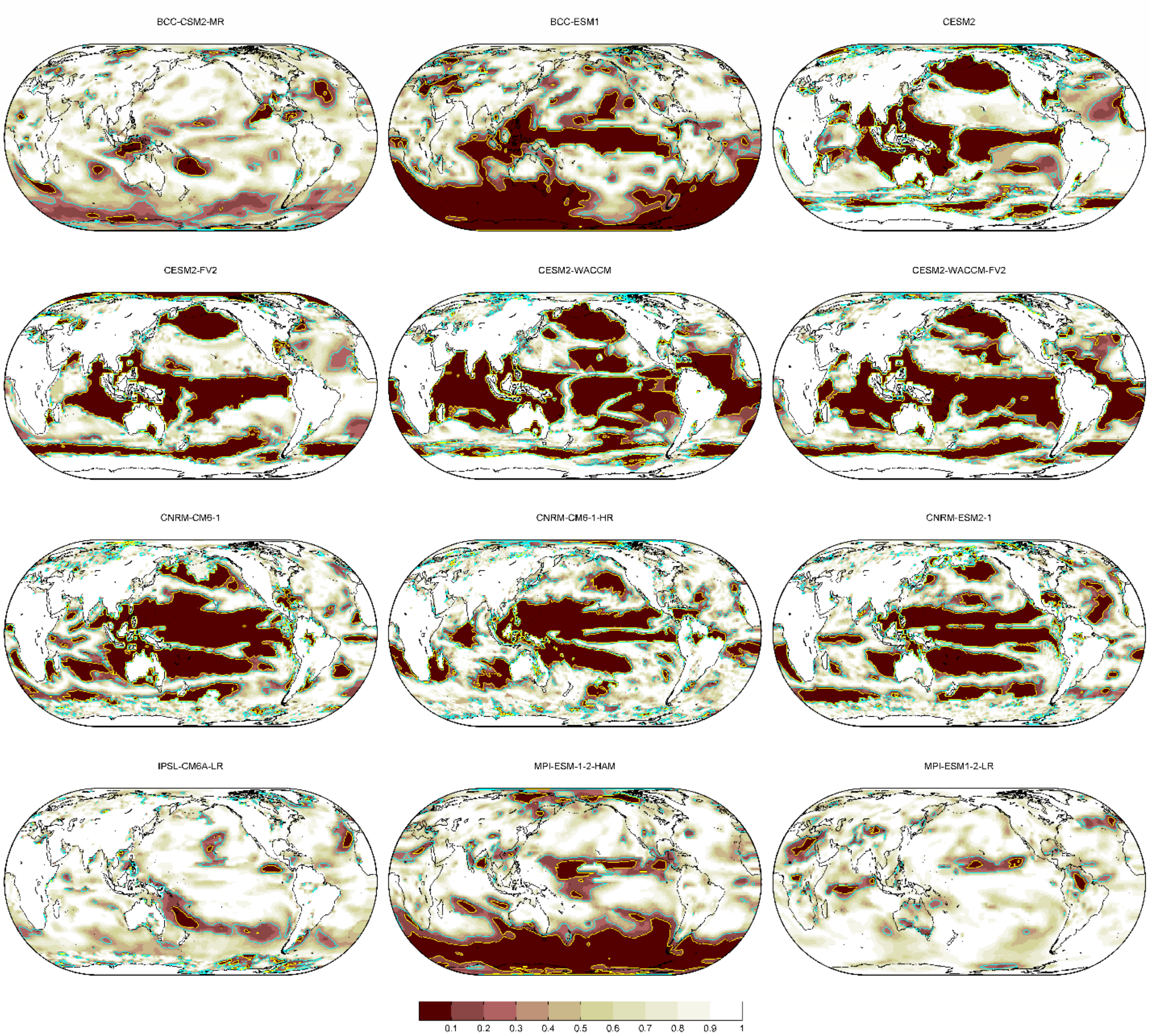

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Figure 3. Probability of no Granger causality from ENSO to annual ozone concentrations at 1000 hPa pressure level for the historical experiment over the 1850-2014 period of 12 individual models (see Table S1). The yellow and cyan contour lines denote p-value = 0.1 and 0.33, respectively. Brown shades imply a low probability of no Granger causality. ENSO: El Niño–Southern Oscillation.

https://doi.org/10.5194/egusphere-2023-207
Preprint. Discussion started: 26 June 2023

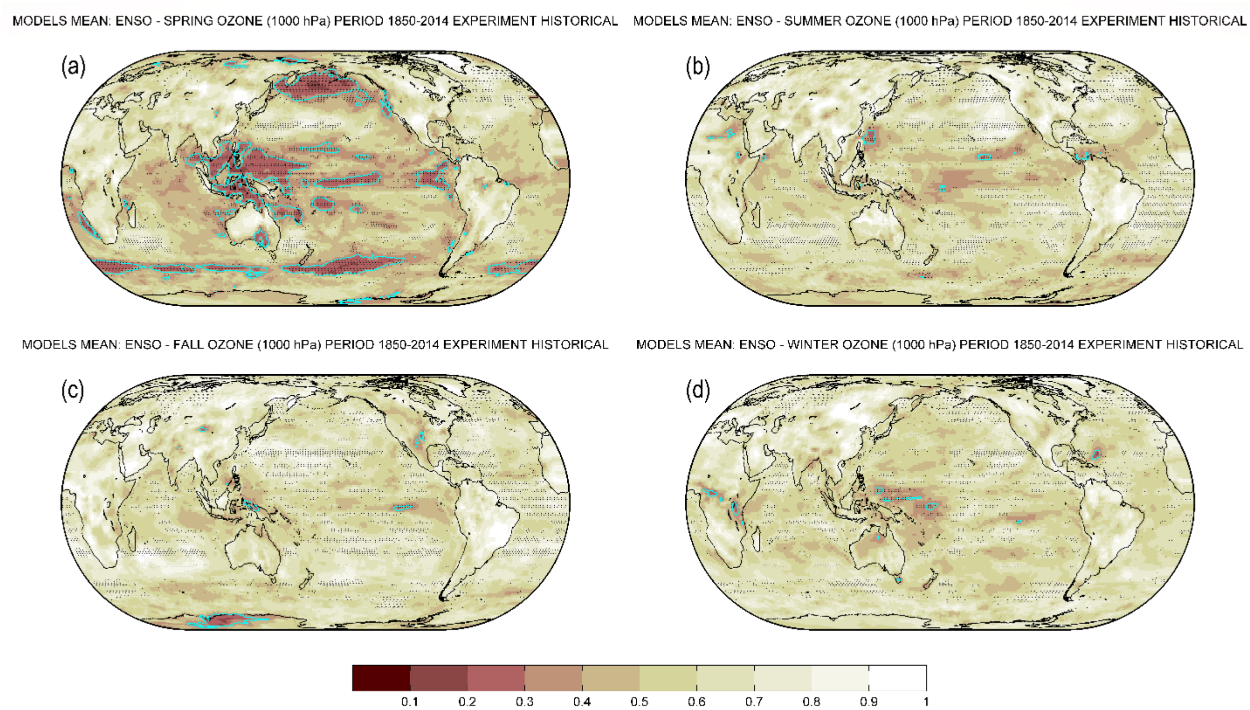

Figure 4. Multi-model mean probability map of no Granger causality from ENSO in boreal winter [D(*t*)JF(*t+1*); *t* indicates year *t*] to seasonal mean ozone concentrations at 1000 hPa pressure level over the period 1850-2014. (a) Spring [MAM(*t+1*)]. (b) Summer [JJA(*t+1*)]. (c) Fall [SON(*t+1*)]. (d) Winter [D(*t+1*)JF(*t+2*)]. Stippling signifies that at least 70% of total models show agreement on the mean probability of all models at a given grid point. The cyan contour line signifies *p*-value = 0.33. Brown shades imply a low probability of no Granger causality. ENSO: El Niño–Southern Oscillation. MAM: March- April-May. JJA: June-July-August. SON: September-October-November. DJF: December-January-February.