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Short Communication

Four decades of climate-driven changes in Northern Hemisphere surface ozone

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A warming climate raises concerns regarding the impact of climate change on air quality. Climate-modulated emissions (e.g., biogenic emissions, lightning and soil NO_x emissions, and wildfires) and conducive weather conditions (e.g., anticyclones, atmospheric stagnation, and heatwaves) can influence both the background ozone level and the production of urban ozone [1–4]. The increased ozone levels threaten public health, crop yields, and the land carbon sink [3]. Previous studies revealed gaps in understanding of how global surface ozone responds to long-term climate change. Specifically, it remains unclear whether historical climate change had already impact on the trend of surface ozone concentration.

Some previous studies demonstrated the climate penalty regarding ozone pollution under both historical climate change and future climate scenarios. Fu and Tai [5] reported that climate change increased summertime ozone in most regions of East Asia by 2–10 ppbv between 1981 and 1985 and 2007–2011 owing to warming-induced changes in meteorological conditions and vegetation. Under future scenarios, climate change is projected to increase surface ozone, especially in regions with high levels of NO_x, which could counteract to some extent the benefits of anthropogenic emission controls [6]. For example, the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6) quantified the impact of global warming of 1 ℃ on ozone levels using the CMIP6 models, and projected notable increase in ozone by approximately 0.2–2.0 ppbv in India and China [7]. However, in other parts of the Northern Hemisphere, such as the United States (US) and Europe, no clear trends in surface ozone are projected under future scenarios of global warming. The regional difference arises mainly from the fact that the IPCC AR6 did not consider fire emissions [2].

Wildfire emissions are increasingly recognized as a critical factor in ozone air quality [8], and their omission might mean that current assessments of the impact of future climate change on ozone might be strongly underestimated. The objective of this study is to investigate the impact of climate change, including fire emissions, on surface ozone from a four-decade perspective (1981–2021). Better understanding of the overall effects of historical climate change on ozone trends across the Northern Hemisphere is particularly essential for improving future projections.

We employ a chemical transport model GEOS-Chem with horizontal resolution of 2° × 2.5° and details of the model settings are provided in the Supplementary material. Two long-term simulation experiments are carried out to estimate the contribution of climate change and fire emissions to surface ozone trends: (1) The AnthFix experiment. Anthropogenic emissions are fixed in 2017, and a GEOS-Chem simulation of 1981–2021 is conducted to estimate the impact of climate change on ozone. (2) The Nofire experiment. We turn off the fire emissions in GEOS-Chem based on the AnthFix experiment and simulate ozone concentrations. The difference between the AnthFix experiment and the Nofire experiment (AnthFix-Nofire) represents the contribution of fire emissions to ozone production. The GEOS-Chem baseline simulation in 2017 shows very good performance in simulating observed summertime MDA8 ozone in 4201 sites across the Northern Hemisphere (Fig. S1 online). Maximum daily average 8-h (MDA8) ozone concentrations are calculated from the simulated hourly ozone data across each 15°N time zone.

Widespread ozone increases by climate change. During 1981–2021, summertime surface air temperature rose by 1.0 °C over

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the Northern Hemisphere continental area, revealing a statistically significant trend in historical climate warming (Fig. S2 online). Fig. 1a shows the total effect of the historical climate on long-term trends of ozone in the Northern Hemisphere based on the 41-year simulation results of the AnthFix run. It is evident that ozone increased widely across the Northern Hemisphere over the past four decades, with mean increase of 0.67 ppbv/10 a (1 ppbv = 10^{-9} m^3/m^3), representing a substantial climate penalty on historical surface ozone. In Asia, Mongolia exhibits the largest rise in ozone concentration, with an upward trend of 1.8 ppbv/10 a, followed by the Russian Far East (0.98 ppbv/10 a) and eastern China (0.71 ppbv/10 a). These findings are consistent with the spatial distribution of an increase in summer surface ozone during 1980–2010 driven by climate change, as reported by Fu and Tai [5]. In Europe, ozone concentration shows an overall statistically significant positive trend, with a regional average of 1.2 ppbv/10 a. In North America, the western US experiences the greatest increase in ozone of 1.6 ppbv/10 a, whereas the eastern US and Canada exhibit no statistically significant trends of change. In comparison to a total ozone increase of 0.2–2.0 ppbv in India and southeastern China under a future 1 °C warming scenario from the IPCC AR6, the GEOS-Chem simulation results driven by a 1 °C warming in the past 40 years of historical climate suggest a broader and more severe climate penalty on ozone.

To quantify the contributions from non-fire climate effects, we turn off the fire emissions in GEOS-Chem, as depicted in Fig. 1b. In the absence of fire emissions, it is evident that the contribution of climate change to ozone concentration is reduced, with a regional average of 0.44 ppbv/10 a, accounting for 66% of the total climate effect. Spatially, the non-fire climate impact diminished to some extent, with the most pronounced effects in the mid-latitude regions of the western US, Europe, Mongolia, and eastern China, where regional contributions were 1.4, 1.1, 1.8, and 0.66 ppbv/10 a, respectively. Additionally, similar patterns in temperature increases in summer are found over the past 40 years, with trends of 0.47 °C/10 a in the western US, 0.49 °C/10 a in Europe, 0.41 °C/10 a in Mongolia, and 0.16 °C/10 a in eastern China (Figs. S2 and S3–S6a online). The ozone changes driven by non-fire climate effects are spatially consistent with the great temperature changes, indicating the important role of climate change in ozone formation through various temperature-dependent processes [1].

We also find indications of the increasing importance of fire emissions to surface ozone trends. It can be seen from Fig. 1c that fire emissions drive an increase of 0.23 ppbv/10 a in surface ozone, accounting for 34% of the total impact of climate change on ozone over the past four decades. It is worth noting that the regions where fire emissions most strongly influence ozone trends do not fully overlap with areas experiencing significant warming, which is different from the effects associated with non-fire climate change. The contribution of fire emissions to MDA8 ozone is particularly pronounced over the Russian Far East, western US, and Canada, with increases of 1.0, 0.28, and 0.53 ppbv/10 a, respectively. And its positive impact on ozone has been well-documented, with multiple models confirming the substantial influence of fire emissions on ozone levels in regions like the western US, Canada, and Russia [9,10]. Compared with the IPCC AR6 estimates

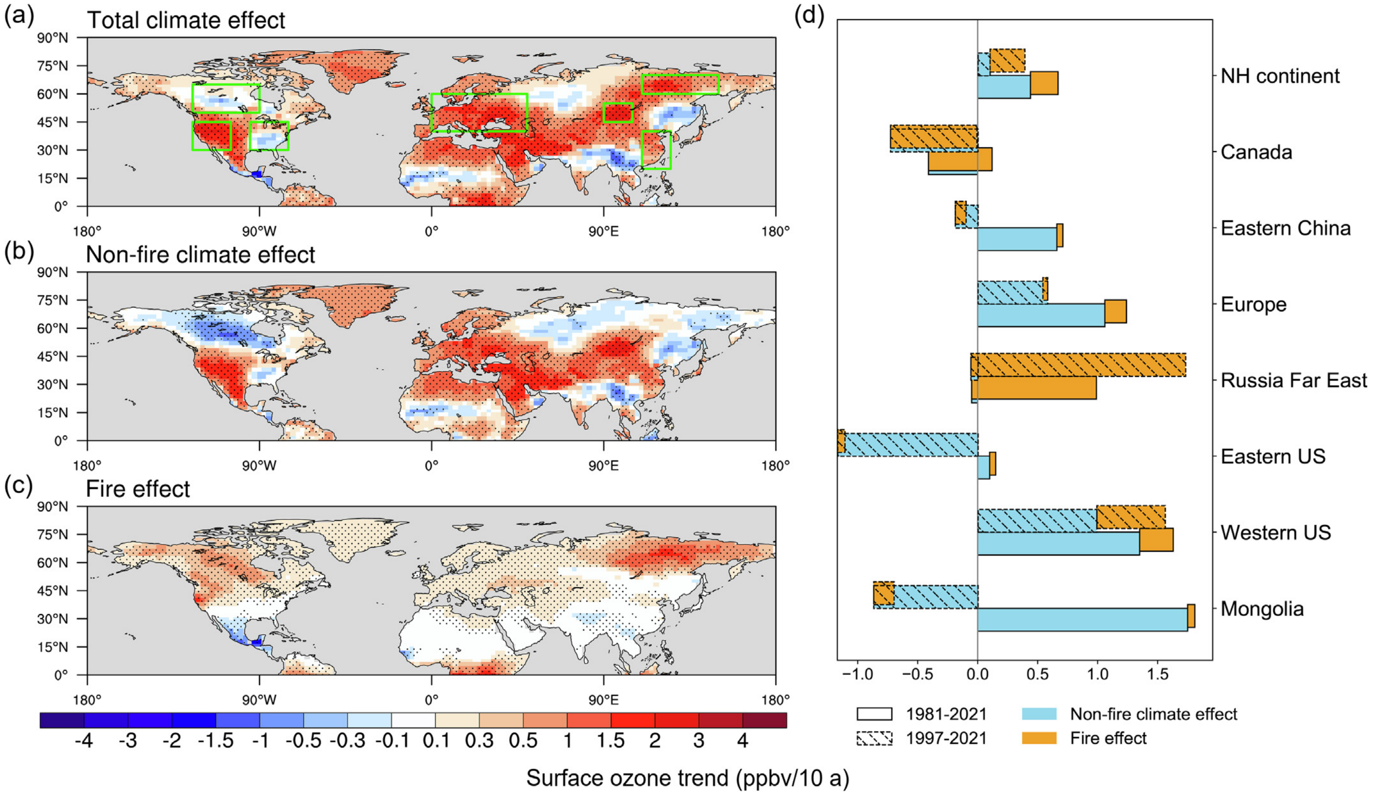

Fig. 1. Surface ozone trends driving by historical climate. (a) The total climate effect (AnthFix experiment), (b) the non-fire climate effect (Nofire experiment), and (c) the fire effect (difference between AnthFix and Nofire experiments) on summertime MDA8 ozone trends (ppbv/10 a) during 1981–2021 in the Northern Hemisphere (NH), with black dots indicating statistically significant trends. Green boxes delineate key regions of Canada (50°–65°N, 90°–125°W), the western US (30°–45°N, 105°–125°W), the eastern US (30°–45°N, 75°–95°W), Europe (40°–60°N, 0°–50°E), Russian Far East (60°–70°N, 110°–150°E), Mongolia (45°–55°N, 90°–105°E), and eastern China (20°–40°N, 110°–125°E). (d) Contribution of climate change to summertime MDA8 ozone trends in the key regions of the Northern Hemisphere, with blue bars representing the non-fire climate effect and orange bars representing the fire effect. The sum of the two bars represents the total climate effect. Bars with solid and dashed lines represent 1981–2021 and 1997–2021, respectively, with the aim of removing potential interference from the two fire emission inventories on ozone trends. The specific values corresponding to each bar are shown in Table S1 (online).

and under the same 1 °C warming, our findings reveal that historical MDA8 ozone over the land areas of the Northern Hemisphere increased by 2.75 ppbv, with fire emissions contributing by 0.94 ppbv. Therefore, neglecting fire emissions would result in a substantial underestimation of the climate penalty on ozone pollution.

Temporal and spatial differences in key regions. The impact of climate change on ozone trends varies greatly both regionally and temporally (Fig. 1d). In the high latitudes of the Northern Hemisphere (Canada and Russia), non-fire climate change led to ozone reduction. The reduction may reflect the fact that a warmer climate with higher relative humidity (Fig. S2b online) and more abundant water vapor in a warmer climate enhance ozone destruction in clean regions [11]. Wildfires, which are prevalent in Canada and the Russian Far East, have offset the decline in ozone attributable to non-fire climate effects over the past 40 years. In eastern China, fire emissions have a minor impact on ozone trend (0.05 ppbv/10 a) due to much lower biomass burning emissions compared to regions like Russian Far East and North America. The simulated increase in ozone concentration can be largely attributed to the non-fire climate effect. Elsewhere, both temperature-driven and fire emissions contribute to the increase in ozone over the western US, but that the contribution of non-fire climate effects is greater due to the large-scale warming (1.5 ℃) in the western US over the past 40 years.

Substantial evidence indicates that the frequency of wildfires has been increasing in recent years [12]. Therefore, the trend of increase in ozone related to wildfires has become better-defined in recent years. For the purpose of temporal comparison, the study period of 1981–2021 was divided into two phases: 1981–1996 and 1997–2021. This is because the year 1997 marks the start of the continuous global fire emission data (GFED4) inventory. During 1997–2021, the trend of ozone driven by fire emissions reached 1.8 ppbv/10 a in Russia, 0.72 ppbv/10 a in Canada, and 0.57 ppbv/10 a in the western US, dominating the climate change contribution in these regions. The result highlights the need to consider the impact of fire emissions on air quality under future warming scenarios. In contrast, the recent contribution of non-fire climate change to ozone has differed from its long-term effect over the past four decades (Fig. 1d). Because the non-fire climate effects on ozone display strong temporal dependence related to decadal temperature fluctuations, particularly in the eastern US and eastern China (Fig. S4c and Fig. S6c online). Under the RCP8.5 scenario, wildfire frequency is projected to increase substantially across 74% of global land areas by the end of the 21st century [13], suggesting increased risk from concurrent heatwaves and wildfires.

Temperature dominates ozone variations under a changing climate. We observe that the summertime temperature of the Northern Hemisphere did not increase continuously during 1980–2021 (Fig. 2a). The slowdown in temperature rise has been reported in the IPCC report, which identified the period of 1998–2012 as a global warming hiatus, with a trend of temperature increase of merely 0.12 °C/10 a compared with the value of 0.25 °C/10 a over the past 40 years. The global warming hiatus was particularly pronounced at the regional level (Figs. S3–S6a online). In the western US and eastern China, the temperature trend during 1998–2012 was only 0.16 °C/10 a and −0.10 °C/10 a, respectively.

This pattern is mirrored in the trend of surface ozone driven by climate change, as shown in Fig. 2b–d. The contribution of the total

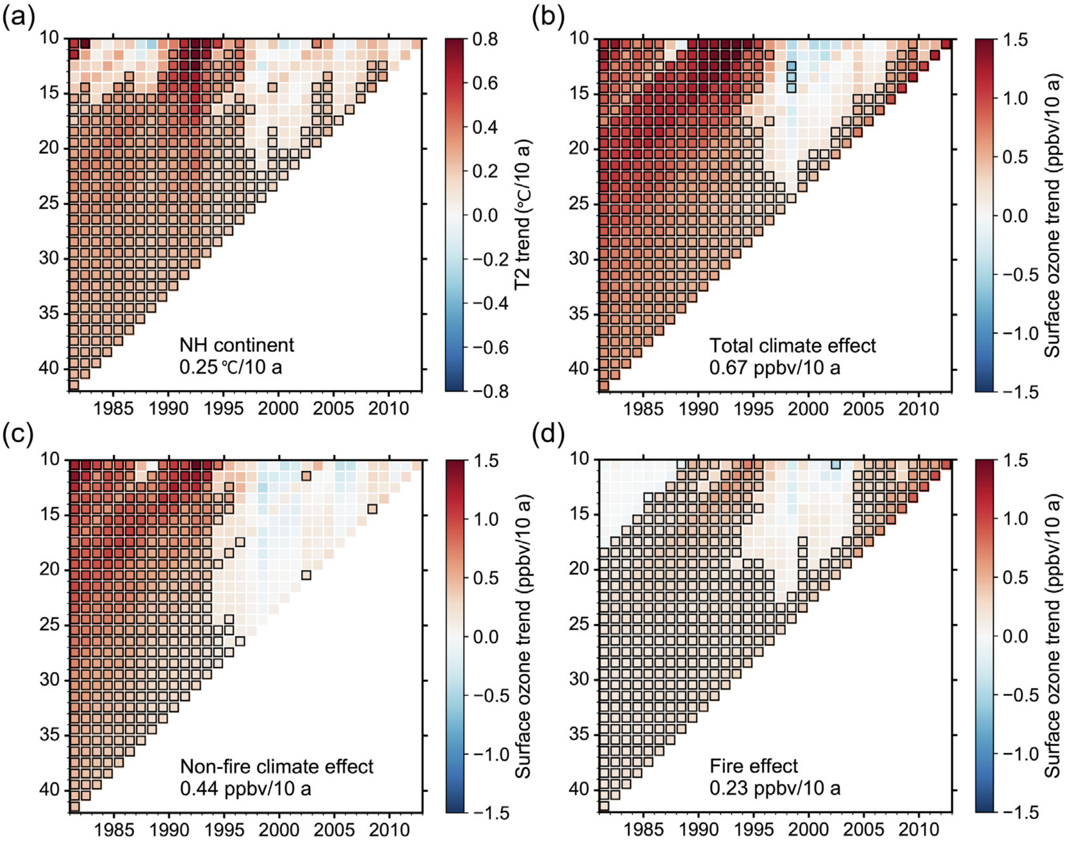

Fig. 2. Response of ozone trend variations to temperature under climate change. (a) Time series of summertime 2-m temperature (T2) trend (°C/10 a) over the continents of the Northern Hemisphere (15°–90°N). The trend at the bottom of the panel represents the 41-year long-term T2 trend from 1981 to 2021. Time series of MDA8 ozone trends (ppbv/10 a) over the continents of the Northern Hemisphere under (b) the total climate effect, (c) the non-fire climate effect, and (d) the fire emission effect. The *x*-axis represents the start year, and the *y*-axis shows the duration over which the trend was calculated from the start year. The color within each square indicates the calculated trend value; squares with black borders represent statistically significant trends ($P < 0.05$).

climate change to the trend of ozone during 1998–2012 was −0.11 ppbv/10 a, i.e., substantially lower than the trend of 0.67 ppbv/10 a in the past 40 years. Similarly, non-fire climate change and fire emissions contributed only −0.03 and −0.07 ppbv/10 a to the trend of ozone during the warming hiatus. This indicates that temperature-related processes dominate ozone concentration in the context of climate change. However, regional analyses (Figs. S3–S6 online) revealed that ozone trends caused by fire emissions do not always align with temperature trends. In the US, the contribution of fire emissions to ozone has increased in recent years, while the non-fire climate effects on ozone display strong temporal dependence related to decadal temperature fluctuations, particularly in the eastern US (Fig. S4c online). The temporal decoupling between fire-induced ozone trends and temperature trends suggests that wildfire emissions and their impacts on ozone are modulated not only by climate but also by human activities, vegetation, and land-use changes [14]. It reminds us to further understand future extreme weather events, which could exacerbate wildfire risks [15] and drive global background ozone levels even higher.

Comparison of modeled climate-driven trends and observed ozone trends. Long-term ozone observation data (Table S2 online) from the US and Europe indicate a decline in the MDA8 ozone during the warm season [3,7]. However, our simulation results suggest that climate change contributed to statistically significant increasing trends in western US (1.63 ppbv/10 a) and Europe (1.23 ppbv/10 a) over the past 40 years, in contrast to the observed decline. This discrepancy can largely be attributed to early emission reduction policies in these countries, which offset the effects of climate change and drove the downward trend in ozone levels. This is supported by the weakening climate penalty during the warming hiatus (Figs. S3 and S5 online) combined with continued emission reductions made the observed ozone decline even more pronounced. Specifically, the 95th percentile ozone levels decreased at rates of −2 to −1 ppbv/a in the US and −0.42 ppbv/a in Europe (Table S2 online). However, since 2014, ozone pollution has intensified in Asia, as well as in the western US and Europe, with the average ozone trend in Europe rising to 0.68 ± 0.12 ppbv/10 a [3]. This shift in developed countries is due to emission reductions reaching a plateau while the impacts of global warming and fire emissions have intensified (Figs. S3 and S5 online), resulting in an observed upward trend in ozone, especially in the western US and Europe. By comparing observed and simulated ozone trends, we highlight that the role of climate change is becoming prominent and expected to play a more substantial role in shaping ozone trends in the future.

In summary, we simulate the impact of historical climate change on summertime surface ozone concentration in the Northern Hemisphere over the past 40 years (1981–2021). Our results show a 1.0 °C (0.25 °C/10 a) rise in temperature, corresponding to an increase of 2.75 ppbv (0.67 ppbv/10 a) in surface ozone concentration. This climate penalty is more severe and regionally widespread than the 0.2–2.0 ppbv ozone increase projected only for India and China by the IPCC AR6 under a scenario of future 1 °C warming. Moreover, the changes in temperature and ozone driven by climate change reveal strong temporal and spatial consistency, confirming that global warming contributes to increasing large-scale ozone levels through temperature-dependent processes. The contribution of fire emissions to the ozone concentration was 0.23 ppbv/10 a, accounting for one third of the total climate effect. In recent years (1997–2021), increased fire emissions dominated the climate-driven ozone trends with a contribution of 75%. These findings emphasize the emerging role of ongoing climate change, and particularly the growing impact of wildfires, in influencing regional ozone-related air quality.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Ke Li and Hong Liao conceived the study. Danyuting Zhang performed the analysis. Yang Yang, Xu Yue, and Wenju Cai contributed to interpreting the data. Danyuting Zhang wrote the draft of the paper with inputs from Ke Li, Hong Liao, and Wenju Cai. All authors contributed to discussing and improving the paper.

Data availability

The MERRA-2 reanalysis data are from https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2. The GEOS-Chem model and emission data are available from https://geoschem.github.io/.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2025.10.029.

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