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Climate Change Penalty to Ozone Air Quality: Review of Current Understandings and Knowledge Gaps

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Abstract

Purpose of Review Climate warming may bear a penalty on future ozone air quality, even in the absence of changes in anthropogenic activities. This penalty has important implications for policy-making, but its quantification involves complex meteorological, chemical, and biological processes and feedbacks that are not well understood. We examined how climate-sensitive processes may affect surface ozone, identified key knowledge gaps uncovered by recent studies, and summarized latest assessments of the climate change penalty on ozone air quality.

Recent Findings Recent analyses have challenged earlier paradigms on how climate change may affect surface ozone. The widely accepted associations of high ozone events with stagnation and heat waves require re-examination. Emission responses of natural precursors to climate warming may be significantly modulated by CO_2 levels and ecosystem feedbacks, such that the direction of emission changes cannot be robustly determined at this time. Climate variability may drive fluctuations in surface ozone, which has implications for near-term air quality management. Recent studies have generally projected a climate change penalty on ozone air quality, although the magnitudes are smaller than those projected by earlier studies.

Summary This review examined the latest understanding on the climate change penalty to surface ozone. Critical uncertainties are associated with the meteorological, chemical, and biological processes linking climate warming and ozone, and many of the known feedbacks are not yet included in models. Further research is needed to examine those processes in order to better quantify the climate change penalty on surface ozone to inform policy-making.

Keywords Ozone · Air quality · Climate change · Climate policy

Introduction

The complex interplay between air pollution and climate change presents a challenge for their prediction and for the assessment of their total risk in the future [1, 2]. Changes in climate conditions will alter the emission, transport, chemical evolution, and removal of air pollutants and their precursors [1, 3, 4]. In turn, ozone (O_3) and fine particulate matter ($PM_{2.5}$), the two major air pollutants, act as near-term climate forcers (NTCFs) that perturb the Earth's radiative energy budgets [1, 3, 5]. Moreover, many air pollutants and their precursors share common anthropogenic sources with major greenhouse gases (GHGs) and are thus concertedly tied to the trajectory of future emission scenarios and climate mitigation strategies [6, 7].

In increasing levels of complexity and human involvement, anthropogenic climate warming, which is driven by increased levels of GHGs, can impact air quality in the following ways:

(a) Through changes in physical climate conditions affecting atmospheric processes, such as temperature, precipitation, humidity, circulation, and actinic flux
(b) Through climate-induced changes in natural emissions of pollutants and their precursors, such as emissions from vegetation, soil, lightning, and wildfires

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(c) Through pollutant produced by increasing atmospheric GHGs, such as the ozone produced by methane
(d) Through climate-induced changes in the land surface and the ecosystem, such as the aridification of land, and the changes in types and densities of vegetation
(e) Through changes in climate-sensitive anthropogenic emissions in the absence of changes in anthropogenic activities, such as the enhanced volatilization of volatile organic compounds (VOCs) from fuels and solvents
(f) Through changes in anthropogenic pollutant emissions due to adaptation or mitigation policies against climate change, such as the increased emissions due to additional energy usage for cooling, the reduced emissions by actively mitigating NTCFs, or the co-reductions in anthropogenic pollutant emissions as a result of GHG mitigation

An important, quantitative diagnostic of the impacts of future climate on air quality is the "climate change penalty," which is the deterioration of air quality due to a warming climate, in the absence of changes in anthropogenic polluting activities [1, 3]. This is often defined as the combined impacts of pathways (a) to (d) above, although the impacts of pathway (e) are sometimes included as well (e.g., [8]). The flip side of the climate change penalty is the "climate control benefit," which is the amelioration in air pollution when climate warming is slowed in the absence of changes in anthropogenic polluting activities [9]. In addition, improvements in air quality can be gained from the co-reduction of anthropogenic pollutant emissions as a result of GHG and NTCF mitigation policies (pathway (f) above), often referred to as the "climate policy co-benefit" to air quality [6, 7, 10]. The sum of the climate control benefit and the climate policy co-benefit represent the total improvement in air quality as a result of climate mitigation, relative to unconstrained climate warming [9]. Many recent studies have shown that capping the global average temperature increase by 2100 to within 1.5 °C or 2 °C of the pre-industrial average can restrain the deterioration of air quality, such that the climate policy co-benefits on regional and global air quality may win out [11••, 12–15]. The associated economic gain in terms of public health and agriculture can offset, potentially completely, the cost of GHG mitigation for both individual nations and the world (e.g., [11••, 12, 13–16]). An integrated mitigation strategy for both air quality and climate is therefore necessary but highlights the need to better quantify the impacts of climate change on air quality.

In particular, the climate change penalty on ozone air quality involves many complex meteorological, chemical, and biological processes and feedbacks, many of which are still not well understood [1, 3]. A large number of recent studies have examined in depth the statistical relationships between ozone and meteorology, as well as the changes in surface ozone in response to climate-sensitive processes in the atmosphere and the ecosystem. In this way, many recent studies have uncovered critical processes that materially altered our understandings of the climate change penalty to surface ozone.

Aims and Scope

In this brief review, we examine the latest understanding on the climate change penalty to surface ozone, with emphases on the underlying processes and knowledge gaps. Table 1 provides an updated summary of the climate-sensitive processes reviewed here, their effects on ozone air quality, and

Table 1 Impacts of climate-sensitive processes on surface ozone over land, updated from Jacob and Winner [17] and Fiore et al. [3] to reflect recent findings

Processes	Level of confidence that warmer climate leads to increase[a]	Impact of increase in process on surface ozone[b]
Tropospheric water vapor	High	-- B
Lightning NO_x	Low	++ B ? LR
Stratospheric ozone transport	Medium	++ B
Background methane	High	++ B
Regional stagnation	Medium	+ LR
Heatwaves	Medium	+ LR
Non-methane BVOC emissions	Low	? B, LR
Soil NO_x	Medium	+ B + LR
Wildfire	Medium	+ B + LR
Dry deposition	Low	-- B, LR

[a] Notations follow those in Fiore et al. [3]: low indicates conflicting evidence on sign of response to a warmer climate; medium indicates some evidence in increase; high indicates well-understood increase

[b] Notations follow those in Fiore et al. [3], which were adapted from Jacob and Winner [17]: ++ consistently positive, + generally positive, – consistently negative in response to an increase in the process, and ? uncertainty of sign of response. B denotes impact on baseline ozone; LR denotes local-to-regional responses

the associate uncertainties. We build on several previous reviews on the subject with regional and global perspectives [1, 3, 4, 17–19] and report mainly on the new findings since 2015. The climate change penalties on $PM_{2.5}$ air quality also involve many of the same processes examined here but are further complicated by opposing influences on the various $PM_{2.5}$ components, as previously reviewed (e.g., [1, 20]). In addition, the atmospheric concentrations and life cycles of many other atmospheric hazardous substances, such as persistent organic pollutants, mercury, and many aeroallergens, are also known to be climate sensitive [17, 21–23]. There may be considerable climate mitigation benefits associated with these hazardous substances that warrant in-depth assessment.

Climate-Sensitive Processes That May Impact Future Ozone Air Quality

Background Tropospheric Chemistry and Ozone Transport from the Stratosphere

Ozone in the troposphere is mainly produced by the oxidation of methane, CO, and non-methane VOCs in the presence of solar radiation and nitrogen oxides ($NO_x \equiv NO + NO_2$), with some transport from the stratosphere. Its removal from the troposphere involves photolysis followed by reaction with water vapor, reactions with HO_2 and OH, and dry deposition to the Earth's surface, resulting in a global mean lifetime of approximately 23 days but with considerable seasonal and spatial variation [5].

Previous studies generally predicted a decline in baseline surface ozone with climate warming, as a result of greater water vapor abundance accelerating ozone chemical loss in the background lower troposphere [1, 3, 24]. However, the rapid increase of global methane levels under the less controlled climate scenarios may raise 2100 baseline surface ozone by as much as 8 ppb, annihilating both the water vapor effect and the efforts of reduced anthropogenic precursor emissions on surface ozone over some regions [5, 25, 26••, 27, 28•, 29•]. In addition, transport of ozone from the stratosphere will likely increase as a consequence of both climate change and the recovery of stratospheric ozone as levels of ozone depleting substances decline [30•]. Under the RCP8.5 scenario, the annual average difference in stratospheric origin ozone concentration at sea level between 2000 and 2100 may exceed 5 ppb in the Southern Hemisphere, over mountainous areas, and over certain regions such as the Mediterranean Basin [30•].

Climate-induced changes in lightning NO_x emissions may affect baseline surface ozone concentrations in complex ways [31•, 32]. On a global scale, sustained enhancement of lightning NO_x emissions will initially increase background ozone, but the associated increase in OH will decrease global methane concentrations, which in turn ultimately reduce background ozone production on decadal timescales [31•]. However, the direction of change of lightning activities in the future remains highly uncertain. A recent study found that the simulated lightning flash densities based on relatively simple parameterizations of cloud top height or cold cloud depth agreed well with the observed spatial distributions of lightning [33]. Predictions based on those two parameterizations projected moderate to large increases in global lightning for future climate conditions. However, another study used a new parameterization that took into account the key effects of cloud ice fluxes and projected a decrease in global lightning under climate warming [34].

Surface Sources/Sinks of Ozone and Its Natural Precursors

Atmosphere–Vegetation Exchange of Ozone and Biogenic VOCs Over vegetated continental areas, surface ozone production is often dominated by the photo-oxidation of biogenic VOCs (BVOCs), which include not only most importantly isoprene (C_5H_8) but also other alkenes, terpenes, and oxygenated VOCs. The emission of BVOCs from plants is highly variable across species and non-linearly dependent on temperature, sunlight, soil moisture, leaf physiology, and other environmental variables [35]. As such, an important way by which climate warming can affect surface ozone is by altering the fluxes of BVOCs. Early studies mostly scaled up leaf-level temperature and solar radiation sensitivities, predicting a large increase in BVOC emissions as a result of climate warming on local to global scales (e.g., [35, 36]).

A growing number of new studies are contesting this paradigm of much higher BVOC emissions in the future when the complex interactions between the biosphere, climate, and surface ozone are taken into account. For example, while future elevated CO_2 concentrations may enhance the global net primary productivity and thus isoprene emissions, they also may "inhibit" isoprene emissions by uncoupling them from photosynthesis, an effect that has been shown to substantially offset or even reverse the sign of future BVOC emission changes on regional and global scales [37, 38•, 39•, 40]. Intra- and interspecies competitions within the ecosystem responding to climate change may also reduce the abundance of high BVOC-emitting species, nullifying the effect of warming on BVOC emissions [39•, 41].

Ozone itself interacts with vegetation to affect the net surface fluxes of BVOCs and ozone. Cumulative stomatal uptake of ozone damages photosynthesis, leading to reduction in leaf area index (LAI), gross primary productivity (GPP), crop yields, and transpiration, ultimately constituting a negative feedback via BVOC emissions [42, 43••, 44•, 45••, 46•, 47••, 48]. At the same time, reduction in LAI slows the dry deposition velocity of ozone via stomatal uptake, constituting a positive feedback [42, 47••, 49]. A model study by Zhou et al. [47••] showed that, on a global scale, the positive

feedback of ozone via its dry deposition out wins the negative feedback via BVOC emissions, particularly over the tropical forests. However, several studies showed that the dry deposition of ozone over many vegetated surfaces may be driven mainly by non-stomatal mechanisms and not by stomatal uptake [50–52], or the stomatal uptake maybe strongly modulated by climate conditions [48]. As such, the positive feedback on ozone may not be as pronounced as modeled by Zhou et al. [47••]. Other feedbacks recently explored included the modified vegetation transpiration feeding back into local climate [44•] and the difference in ozone tolerance leading to competition within the ecosystem [53]. Overall, it has become clear that the response of vegetation to climate change and ozone stress is too uncertain to reliably predict the change in future BVOC emissions and ozone deposition.

Soil Emission of NO_x In addition to the emissions of BVOCs, the chemical and microbial emissions of NO_x from soils are also highly sensitive to meteorological variables [54]. The impacts of the soil NO_x climate sensitivity on the climate change penalty of surface ozone have so far largely been overlooked, but they may become increasingly important as anthropogenic NO_x emissions continue to decline over many areas. An example of this was over the Southeast USA, where one analysis showed that the ozone enhancements on hotter days were mainly driven by changes in local chemistry, with an integrated ozone–temperature sensitivity of 2.3 ppb K^{-1} [55•]. Nearly half of that ozone–temperature sensitivity was attributable to temperature-enhanced soil NO_x emissions of 0.23 ng N m^{-2} s^{-1} K^{-1}, most likely by soil microbes [55•]. Most current models still use an empirical parameterization developed in the 1990s to compute soil NO_x emission as a linear function of temperature and a step function of precipitation [56]. However, the soil NO_x fluxes thus computed were significantly lower than those derived from satellite- and ground-based measurements and misrepresented the observed spatiotemporal patterns [57]. Hudman et al. [54] developed a more mechanistic parameterization for soil NO_x emission that is non-linearly dependent on soil temperature, soil moisture, soil wetting by precipitation after a drying period, as well as the soil nitrogen content from deposition and fertilizer application [54]. They found that this new parameterization better reproduced the magnitude and the spatiotemporal of tropospheric NO_x columns observed from space [54]. However, the impacts of this new parameterization on the climate change penalty of surface ozone have not yet been explicitly evaluated.

Wildfire Emissions of Ozone Precursors Wildfires are strong sources of ozone precursors [46•, 58, 59•], and climate change alone will likely increase the global risks of wildfires in the future [58, 60••, 61]. Changes in climate conditions alter the abundance, distribution, and aridity of vegetation biomass available for burning, as well as the natural ignition, spread, and intensity of wildfires [58, 62]. Many analyses of satellite and ground-based fire observations have found marked increases in regional wildfire activities in recent decades attributable to climate warming, including in particular over the western USA [63, 64], where wildfire emissions currently contribute 2–8 ppb of summertime monthly mean ozone at individual sites [59•]. In contrast, the historic emission inventory recently compiled for the Coupled Model Intercomparison Project Phase 6 (CMIP6) showed relative stable global biomass burning emissions between 1750 and 2015 despite pronounced global warming [65], but the lack of robust fire data during the early periods may have confounded that estimate. A recent study diagnosed the fire weather index (FWI) in 17 simulations of historical climates and future climates under the RCP8.5 scenario [60••]. Relative to historical conditions (1861 to 2005), that study showed a distinct increase in the number of high FWI days over 22% of the world's burnable land area by 2019, including over the Amazon. By the mid-twenty-first century, the number of high FWI days was found to increase over 62% of the world's burnable lands, including much of North America, Europe, and South China. Increases in the daily maximum temperature and decreases in relative humidity were found to be the dominant driver for the future increase in fire risks [60••].

More uncertainties arise when the dynamic interactions between fire, climate, air quality, and the terrestrial ecosystem are considered [58, 62]. Fires modify the structure and distribution of the terrestrial ecosystem and feedback to the atmosphere via changed albedo, ecosystem properties, transpiration, and emissions of BVOC, GHG, and other trace species [58, 62, 66, 67]. In addition, fire-induced surface ozone pollution may significantly contribute to the ozone damage of global terrestrial productivity, potentially forming a negative feedback [46•]. Investigations of these complex air quality–climate–ecosystem interactions and their impacts on wildfires and ozone have only just begun [46•, 62].

Photochemistry of Ozone Formation

Even if the emissions of biogenic VOCs do increase with climate warming, the associated response of surface ozone over BVOC-rich areas is still quantitatively uncertain [68]. A canonical example of this is the Southeast USA, where model studies disagreed on even the sign of surface ozone change due to warming-enhanced isoprene emissions [1, 17]. This lack of consensus has been mainly attributed to the different model assumptions on the yields of isoprene nitrates and their subsequent NO_x-recycling ratios [3, 17, 68], as the formation of non-NO_x-recycling isoprene nitrates terminally removes NO_x from the photochemical reactions leading to ozone formation. Over the last decade, great progress has been made in laboratory and field experiments regarding the

photochemistry of isoprene [69, 70]. The yields of isoprene nitrates are now better constrained at about 12–16% and their subsequent NO_x-recycling ratios at about 50% [69, 70], but not all models have been updated to reflect these changes [68, 71]. In addition, it has been shown that the effects of these photochemical parameters in models are resolution-dependent, as they partially compensate for the artificial mixing between NO_x and isoprene in coarser resolution models [72, 73]. As such, the laboratory-derived values for these parameters may not be directly applicable in models. One recent study pointed out that the interannual variation of August temperature over the Southeast USA between 1988 and 2011 manifested a continental-scale temperature oscillation, which provided an opportunity to diagnose the response of surface ozone to large-scale warming [74••]. That study concluded that surface ozone does increase in response to the enhanced isoprene emissions driven by large-scale warming and that the observed ozone–isoprene sensitivity was consistent with a 12% first-generation yield and a 55% subsequent NO_x-recycling ratio for isoprene nitrate for their model at 2.5° longitude × 2° latitude resolution.

Synoptic- to Seasonal-Scale Meteorology

Over polluted areas, high levels of surface ozone have often been shown to correlate with individual local meteorological variables, such as warm temperature, strong solar radiation, low relative humidity, and low precipitation, on synoptic and seasonal timescales (e.g., [75••, 76••, 77•, 78•, 79, 80]). These correlations form some evidence that changes in regional meteorology due to climate warming will likely incur changes in future surface ozone. However, as these local, short-term correlations do not indicate actual causal processes, they cannot be directly extrapolated to estimate surface ozone in future climate. Instead, much effort has been in identifying the synoptic weather patterns that drive surface ozone variability and the observed correlations between ozone and meteorological variables, with the goal of quantifying the changes of those weather events in future climate to predict surface ozone change (e.g., [81–85]).

Many such synoptic and seasonal-scale weather patterns have been identified as partial drivers for high surface ozone, and the potential changes in some of those weather patterns in future climate have been explored. Over eastern North America, the variability of summertime surface ozone depends strongly on the north–south shift of the polar jet and the westward extension of the Bermuda High [86•, 87•]. Severe drought conditions have also been shown to enhance summertime US surface ozone by 3.5 ppb [79], and an increase of 1–6% for surface ozone has been estimated by 2100 compared to the 2000s due to increasing drought alone [79]. Over Europe and the UK, anti-cyclonic conditions, easterlies, blocking, and subtropical ridges have all been shown to significantly enhance surface ozone [81, 83, 84]. Over eastern China, ozone pollution events are often linked to the anti-cyclonic conditions or atmospheric subsidence associated with the Pacific Subtropical High [82]. Over coastal southern China, high ozone events are often associated with the subsidence ahead of an approaching tropical cyclone [85]. As a result, changes in tropical cyclone numbers and trajectories in the future will potentially both impact local ozone air quality, although those metrics are difficult to predict in climate models [85].

A condition commonly coupled to many of the weather events above is regional air stagnation, which has been widely accepted as a large driver for the observed positive ozone–temperature sensitivity [3, 78•, 88•, 89, 90]. Regional stagnation often occurs under the influence of anti-cyclonic air masses and subsidence, and in that way, stagnation may be correlated with high temperature, shallower mixing layer, less cloud cover, less precipitation, and strong radiation. Mechanistically, stagnation suppresses the horizontal and vertical ventilation of ozone and its precursors from the boundary layer and can thus build up surface ozone [71]. A number of studies have characterized future stagnation occurrences using the Air Stagnation Index (ASI), which is a Boolean index defined by light winds near the surface and in the mid-troposphere and no precipitation [91, 92]. These studies generally found more frequent stagnation occurrences in the future and implied a potential worsening of ozone air quality [91, 92]. However, recent analyses found that the observed summertime surface ozone and high ozone events were only weakly correlated against either the ASI or the number of stagnant days over the USA on both daily and seasonal scales [75••, 93•, 94••, 95]. In addition, no positive correlation was found between daily temperature and the ASI [95]. As such, the use of ASI as a predictor for present or future levels of surface ozone appears not to be sound. It is yet unclear why the ASI is not significantly correlated with surface ozone and temperature. It may be that the meteorological variables that define the ASI (light wind and no precipitation) do not capture the actual "stagnant" conditions leading to high surface ozone [95]. Alternatively, it is possible that suppressed ventilation is simply not a key driver for high ozone, nor is it a key driver for the observed ozone-temprature sensitivity.

Early model studies showed that climate warming can lead to preferential increases in the high-end of the ozone probability distribution, which has been widely attributed to more frequent occurrences of extreme high temperature and heat waves in the future [3, 17]. Much attention has thus been directed at the association of extreme ozone pollution with extreme warmth or heat wave occurrences, as the combined stress may produce disproportionally serious public health risks [77••, 88•, 93•, 96, 97, 98••]. Some observational analyses over the USA showed that the ozone–temperature sensitivities are larger at higher ozone quantiles [76••], while the

probability of summertime severe ozone pollution when there are heat waves could be up to seven times of the average probability [93•]. A model simulation for present-day climate also showed enhancements of surface ozone exceeding 10 ppb over eastern USA, Europe, and China on heat wave days relative to non-heat wave days [99]. Schnell and Prather [88•] showed that extreme events of ozone and temperature over North America do generally overlap, but their occurrence shows consistent offsets in space and in time, possibly reflecting the response scale and time of natural precursor emissions and pollutant advection [88•].

However, other recent observations and model analyses showed muted sensitivities of ozone to temperature on the higher end of their probability distributions [100] and no preferential increase in extreme ozone probability associated with heat wave days on the interannual timescale [94••]. One model projection indicated slight decreases in ozone over the Southeast USA on heat wave days in the future, despite that model showing large ozone enhancements over the same region on heat wave days for the present climate [99]. Thus, the connection between extreme ozone and extreme temperature may not be as robust as previously believed. Possible explanations may involve chemical and biophysical feedbacks, such as the diminished role of nitrogen oxide sequestration by peroxyacetyl nitrates and the reduced biogenic isoprene emissions at high temperatures [101]. Interestingly, two recent studies, based on observations and simulations, respectively, found larger ozone enhancements associated with the co-occurrence of heat wave and stagnation events than when either of those events occur in isolation [93•, 98••]. This may provide an explanation as to why the ASI or the heat wave occurrence individually is not robust predictors of high surface ozone.

Another newly proposed way by which climate change affect surface ozone is by lengthening the local ozone season [102••]. Zhang and Wang [102••] showed that the high ozone observed over the Southeast USA in October 2010 was driven by the abnormally warm and dry conditions that fall, which enhanced biogenic isoprene emissions, photochemical production, air stagnation, and fire emissions. They pointed out that the further warming and drying of fall climate over the Southeast USA in the future, as projected by climate models, will likely deteriorate seasonal ozone air quality [102••]. This seasonal effect of climate change on ozone can presumably also happen over other vegetated areas.

Interannual and Interdecadal Climate Variability

Several modes of natural climate variability on interannual, decadal, and multidecadal timescales have been shown to influence regional surface ozone, possibly through their impacts on regional meteorology [74••, 103•], wildfires [104], long-range transport [105], and ozone transport from the stratosphere [106, 107]. While these internal variability modes may not be GHG forced, their modulation of surface ozone concentrations in the coming years and decades is extremely relevant for near-term air quality–climate policy-making [108••, 109••]. Over the USA, the warmer, drier, and more stagnant weather, as well as the anomalous circulation patterns during the warm phase of the Atlantic Multidecadal Oscillation (AMO), has been shown to enhance observed summertime surface ozone by 1–4 ppb relative to the cold phase [103•]. Observed surface ozone over northeastern USA has also been shown to correlate with the Arctic Oscillation (AO), the Pacific Decadal Oscillation (PDO), and the Quasi-Biennial Oscillation (QBO) [75••]. Over Southeast Asia, the hot and dry conditions during strong El Niño years can lead to intense fires, which in turn can enhance annual mean surface ozone by 50 ppb near fire sources [104]. Analyses of satellite observations showed that the interannual variability of the tropospheric column ozone (TCO) over the tropics and many mid-latitude areas can be largely explained by El Niño–Southern Oscillation (ENSO) [107], and some of that ENSO influences on the TCO are manifested in surface ozone [106, 110].

Chemistry–Climate Model Projections of the Climate Change Penalties on Ozone Air Quality

Finally, Fig. 1 shows the projections of the climate change penalties on the ozone air quality in polluted regions reported by chemistry–climate model studies published since 2015 (further details are summarized in Table S1). The purpose of this summary is twofold: (1) to compare with previous reviews [3, 17, 120] to examine whether there have been material changes in regional model projections and (2) to identify regions with large changes or uncertainties to direct future research. Almost all recent studies summarized in Fig. 1 focused on North America or Europe; the exceptions were one study over East Asia [117•], one study over India [118•], one study for the globe [24], and one study that analyzed the results from four global models over North America, Europe, and East Asia [119••].

An important implication for the ozone modulation by climate variability is that interpretation of observations and simulations to diagnose ozone trends forced by changes anthropogenic climate warming must be done with caution [108••, 109••, 121]. Early model assessments of the climate change penalty on surface ozone did so by comparing ozone differences between a future time slice against the present-day time slice, averaging the simulations over 3–5 years to represent each time slice [3, 17]. Recent studies showed that at least 15-year averaging windows are required smooth out the "noise" due to natural climate variabilities and to distinguish signals forced by anthropogenic climate warming [8, 109••]. As a result, most studies reported in Fig. 1, although not all of them,

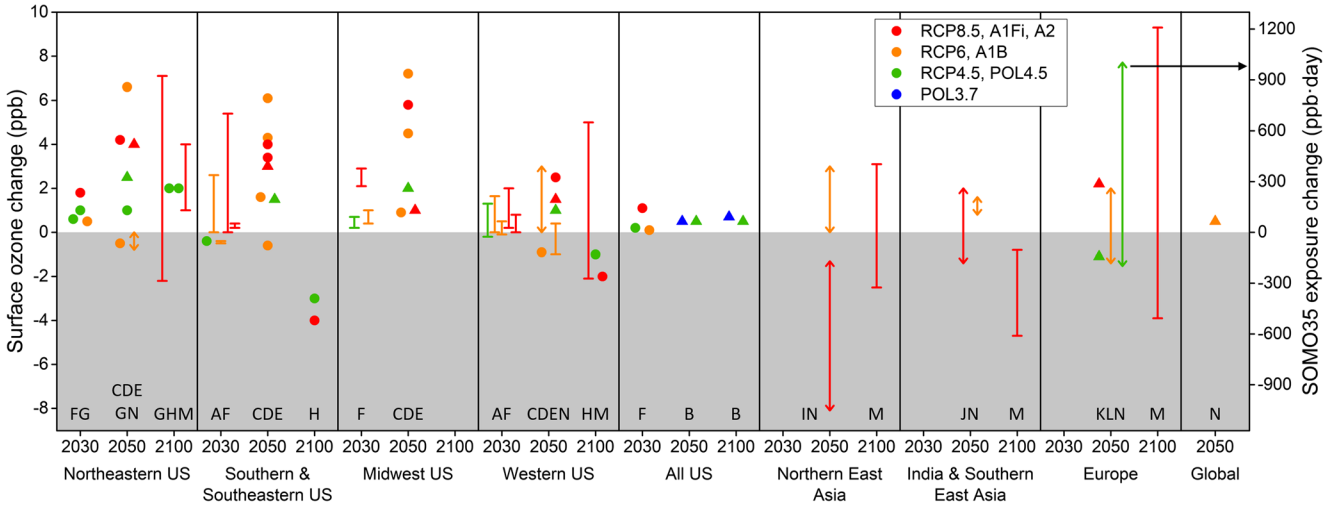

Fig. 1 Model projections of changes in summertime or annual mean ozone air quality due to climate change only, reported in recent studies. This figure is adapted and updated from Jacob and Winner [1] and Fiore et al. [2]. Individual studies are indicated by alphabets: A [111•], B [11••], C [112•], D [113•], E [114•], F [115•], G [116•], H [28•], I [117•], J [118•], K [8], L [26••], M [119••], and N [24]. Climate scenarios are indicated by color: POL3.7 (blue); RCP4.5 and POL4.5 (green); RCP6 and A1B (orange); RCP8.5, A1Fi, and A2 (red). Most studies reported changes (symbols) or range of changes (bars) in mean ozone concentrations or maximum daily 8-h average ozone concentrations averaged over June–August (circles and solid line bars) or averaged over the full year (triangles and dashed line bars). One study [26••] reported changes in the sum of daily mean ozone concentration over 35 ppb (SOMO35). Further details of these recent studies are summarized in Table S1

used 10- to 30-year simulations to represent the ozone air quality of a particular time slice. In addition, Barnes et al. [108••] showed that simulated trends of surface ozone robustly attributable to climate warming alone may not emerge above the noise driven by internal variability until after 2050. Also, chemistry–climate models need to be properly initialized for multidecadal variabilities (e.g., AMO) or use initial condition ensembles to represent the uncertainties associated natural variabilities [74••, 109••].

Over North America, a previous summary [17] concluded that surface ozone will generally increase by 1–10 ppb in response to climate warming, particularly over present-day high-ozone areas such as Northeastern USA. Significant declines in future ozone were only predicted by some models over the Southeastern USA, where the assumptions associated with isoprene nitrate chemistry have great impacts on the simulated response of ozone to warming-enhanced isoprene emissions, as discussed above [17]. Most of the recent studies reported in Fig. 1 also projected rising future surface ozone concentrations, with the larger amounts of ozone increases associated with more significant warming. However, the projected ozone increases up to 7 ppb were more moderate compared to those projected by earlier studies [11, 111•, 112•, 113•, 114•, 115•]. The reason for the smaller ozone changes in recent studies may be that the uses of longer averaging windows smooth out the ozone fluctuations driven by internal climate variability. In addition, recent studies mostly predicted largest ozone increases occurring over the Midwest [11, 111•, 112•, 113•, 114•, 115•], although the reason for this is yet unclear. Notable exceptions were the projections by Rieder et al. [28•, 116•] and Schnell et al. [119••]. Rieder et al. [28•, 116•] found that future ozone will increase over Northeastern USA but will decrease significantly over Southeastern USA and Western USA. However, their model did not include temperature-sensitive BVOC emissions. Three of the four global models in Schnell et al. [119••] also did not include temperature-sensitive BVOC emissions and predicted varying directions of ozone change; the one model that did include temperature-sensitive BVOC predicted large ozone increase throughout the USA. Interestingly, Val Martin et al. [113•] argued that the CO_2 inhibition of isoprene emissions will likely substantially reduced the role of isoprene in the climate change penalty on ozone. As a result, they did not consider temperature-sensitive BVOC emissions in their simulations but still predicted increased future ozone throughout USA due to changes in meteorology alone [113•].

Over East Asia, Lee et al. [117•] simulated the impacts of climate warming on surface ozone but ignored the temperature sensitivity of BVOC emissions. They found a large decrease in annual mean ozone concentrations, particularly over Northeastern Asia, due to projected increase in precipitation and cloud coverage. Over India, Pommier et al. [118•] projected a significant increase in surface ozone of + 2 ppb over Northern India and a decrease of − 1.4 ppb over Southern India. They attributed this regional contrast to climate-induced changes in stomatal conductance in their model, which in turn led to changes in the dry deposition velocity of ozone.

Over Europe, a previous synthesis of 25 model projections found that climate warming will likely bear a penalty on surface ozone over most parts of continental Europe while slightly reducing ozone in Scandinavia in the future [120]. A similar latitudinal dependence of future ozone change in response to

climate warming was also projected in two recent studies [8, 26••]. This latitudinal dependence of ozone sensitivity was likely driven by changes in BVOC emissions, as only the one global model with temperature-sensitive BVOC emissions in Schnell et al. [119•] showed a similar pattern. That global model also found dramatic delays in the seasonal timing of peak ozone by 18 to 60 days over Southern Europe, Eastern USA, and Southern California, possibly driven by enhanced isoprene emissions due to warmer and drier conditions in future falls [102••].

Finally, the two recent global studies both found general increases in surface ozone in a warming climate over mid-latitude continental areas if temperature-sensitive BVOC emissions were taken into account, but neither studies included the CO_2 inhibition on BVOC emissions [24, 119••]. Schnell et al. [119••] found an increase in wintertime surface ozone over the Northern mid-latitude oceans, presumably due to enhanced ozone transport from the stratosphere. In summer, they found consistent decreases in surface ozone over the Northern hemispheric oceans as a result of increased water vapor. In contrast, Glotfelty et al. [24] found an increase in global surface ozone (global average 0.6 ppb) due to climate warming, including over most parts of the global ocean. Significant reduction in surface ozone due to water vapor increases was only found over the tropical ocean and some tropical land areas [24].

The examination of Fig. 1 and comparison against earlier studies indicate that current models generally projected deteriorating surface ozone air quality in the future, but the amount of deterioration attributable to climate change may be smaller than previous assessments due to the noise from climate variability. In addition, the climate change penalty on ozone is very much dependent on the sensitivity of BVOC emissions to climate change. It is important to note that none of the more complex atmosphere–ecosystem feedbacks reviewed in this paper, such as the CO_2 inhibition of isoprene emissions, the ozone damage of leaf and photosynthesis, and the dynamical changes of plant species, in response to climate, ozone, and fire stress, were taken into account in the projections reported in Fig. 1.

Conclusions

This review examined recent studies on the impacts of climate warming on ozone air quality and identified critically uncertain processes that impede the robust quantification of the climate change penalty on surface ozone. The complex ecosystem feedbacks in response to climate warming, rising CO_2 levels, ozone pollution, and other environmental stresses may materially alter natural precursor emissions in the future, but the directions of changes cannot be robustly determined at this time. Previously accepted associations between high ozone events with stagnation and heat waves require further examination. In addition, natural climate variability may drive large fluctuations in surface ozone and may obscure the warming-forced signal until the latter half of the twenty-first century. Recent literatures generally project a climate change penalty on ozone air quality, although the magnitudes are smaller than those projected by earlier studies. However, many of the known processes and feedbacks have not been taken into account in the recent projections. These key knowledge gaps require further study and representation in models to better quantify the climate change penalty on surface ozone to better inform air quality and climate policy-making.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that there is no conflict of interest.

References

Papers of particular interest, published recently, have been highlighted as:
- • Of importance
- •• Of major importance

1. Fiore AM, Naik V, Leibensperger EM. Air quality and climate connections. J Air Waste Manage Assoc. 2015;65(6):645–85. https://doi.org/10.1080/10962247.2015.1040526.
2. Silva RA, West JJ, Lamarque JF, Shindell DT, Collins WJ, Dalsoren S, et al. The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble. Atmos Chem Phys. 2016;16(15):9847–62. https://doi.org/10.5194/acp-16-9847-2016.
3. Fiore AM, Naik V, Spracklen DV, Steiner A, Unger N, Prather M, et al. Global air quality and climate. Chem Soc Rev. 2012;41(19):6663–83. https://doi.org/10.1039/c2cs35095e.
4. Kleinman MT, Bachman JD, Feldman HJ, McCabe D, West JJ, Fiore AF. Connecting air quality and climate change. J Air Waste Manage Assoc. 2015;65(11):1283–91. https://doi.org/10.1080/10962247.2015.1095599.
5. IPCC. Climate change 2013:the physical science basis. Cambridge and New York: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press; 2013.
6. Rao S, Klimont Z, Smith SJ, Van Dingenen R, Dentener F, Bouwman L, et al. Future air pollution in the shared socio-

economic pathways. Glob Environ Change-Human Policy Dimens. 2017;42:346–58. https://doi.org/10.1016/j.gloenvcha.2016.05.012.
7. Fujimori S, Hasegawa T, Ito A, Takahashi K, Masui T. Gridded emissions and land-use data for 2005-2100 under diverse socioeconomic and climate mitigation scenarios. Sci Data. 2018;5:13. https://doi.org/10.1038/sdata.2018.210.
8. Lacressonniere G, Foret G, Beekmann M, Siour G, Engardt M, Gauss M, et al. Impacts of regional climate change on air quality projections and associated uncertainties. Clim Chang. 2016;136(2):309–24. https://doi.org/10.1007/s10584-016-1619-z.
9. West JJ, Smith SJ, Silva RA, Naik V, Zhang YQ, Adelman Z, et al. Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. Nat Clim Chang. 2013;3(10):885–9. https://doi.org/10.1038/nclimate2009.
10. Reis LA, Drouet L, Van Dingenen R, Emmerling J. Future global air quality indices under different socioeconomic and climate assumptions. Sustainability. 2018;10(10):27. https://doi.org/10.3390/su10103645.
11.•• Garcia-Menendez F, Saari RK, Monier E, Selin NE. US Air Quality and health benefits from avoided climate change under greenhouse gas mitigation. Environmental Science & Technology. 2015;49(13):7580–8. https://doi.org/10.1021/acs.est.5b01324. **This article examined the effect of climate change on U.S. air quality and public health under three internally consistent socioeconomic scenarios.**
12. Watson L, Lacressonniere G, Gauss M, Engardt M, Andersson C, Josse B, et al. Impact of emissions and +2 degrees C climate change upon future ozone and nitrogen dioxide over Europe. Atmos Environ. 2016;142:271–85. https://doi.org/10.1016/j.atmosenv.2016.07.051.
13. Shindell D, Faluvegi G, Seltzer K, Shindell C. Quantified, localized health benefits of accelerated carbon dioxide emissions reductions. Nat Clim Chang. 2018;8(4):291. https://doi.org/10.1038/s41558-018-0108-y.
14. Vandyck T, Keramidas K, Kitous A, Spadaro JV, Van Dingenen R, Holland M, et al. Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges. Nat Commun. 2018;9:11. https://doi.org/10.1038/s41467-018-06885-9.
15. Xie Y, Dai HC, Xu XH, Fujimori S, Hasegawa T, Yi K, et al. Co-benefits of climate mitigation on air quality and human health in Asian countries. Environ Int. 2018;119:309–18. https://doi.org/10.1016/j.envint.2018.07.008.
16. Zhang YQ, Smith SJ, Bowden JH, Adelman Z, West JJ. Co-benefits of global, domestic, and sectoral greenhouse gas mitigation for US air quality and human health in 2050. Environ Res Lett. 2017;12(11):11. https://doi.org/10.1088/1748-9326/aa8f76.
17. Jacob DJ, Winner DA. Effect of climate change on air quality. Atmos Environ. 2009;43(1):51–63. https://doi.org/10.1016/j.atmosenv.2008.09.051.
18. Isaksen ISA, Granier C, Myhre G, Berntsen TK, Dalsoren SB, Gauss M, et al. Atmospheric composition change: climate-chemistry interactions. Atmos Environ. 2009;43(33):5138–92. https://doi.org/10.1016/j.atmosenv.2009.08.003.
19. von Schneidemesser E, Monks PS, Allan JD, Bruhwiler L, Forster P, Fowler D, et al. Chemistry and the linkages between air quality and climate change. Chem Rev. 2015;115(10):3856–97. https://doi.org/10.1021/acs.chemrev.5b00089.
20. Fuzzi S, Baltensperger U, Carslaw K, Decesari S, van Der Gon HD, Facchini MC, et al. Particulate matter, air quality and climate: lessons learned and future needs. Atmos Chem Phys. 2015;15(14):8217–99. https://doi.org/10.5194/acp-15-8217-2015.
21. Nadal M, Marques M, Mari M, Domingo JL. Climate change and environmental concentrations of POPs: a review. Environ Res. 2015;143:177–85. https://doi.org/10.1016/j.envres.2015.10.012.
22. Reinmuth-Selzle K, Kampf CJ, Lucas K, Lang-Yona N, Fröhlich-Nowoisky J, Shiraiwa M, et al. Air pollution and climate change effects on allergies in the anthropocene: abundance, interaction, and modification of allergens and adjuvants. Environ Sci Technol. 2017;51(8):4119–41. https://doi.org/10.1021/acs.est.6b04908.
23. Obrist D, Kirk JL, Zhang L, Sunderland EM, Jiskra M, Selin NE. A review of global environmental mercury processes in response to human and natural perturbations: changes of emissions, climate, and land use. Ambio. 2018;47(2):116–40. https://doi.org/10.1007/s13280-017-1004-9.
24. Glotfelty T, Zhang Y, Karamchandani P, Streets DG. Changes in future air quality, deposition, and aerosol-cloud interactions under future climate and emission scenarios. Atmos Environ. 2016;139:176–91. https://doi.org/10.1016/j.atmosenv.2016.05.008.
25. Revell LE, Tummon F, Stenke A, Sukhodolov T, Coulon A, Rozanov E, et al. Drivers of the tropospheric ozone budget throughout the 21st century under the medium-high climate scenario RCP 6.0. Atmos Chem Phys. 2015;15(10):5887–902. https://doi.org/10.5194/acp-15-5887-2015.
26.•• Fortems-Cheiney A, Foret G, Siour G, Vautard R, Szopa S, Dufour G, et al. A 3 degrees C global RCP8.5 emission trajectory cancels benefits of European emission reductions on air quality. Nat Commun. 2017;8:6. https://doi.org/10.1038/s41467-017-00075-9. **This article examined the effects of a +3oC warmng on European ozone air quality.**
27. Jaidan N, El Amraoui L, Attie JL, Ricaud P, Dulac F. Future changes in surface ozone over the Mediterranean Basin in the framework of the Chemistry-Aerosol Mediterranean Experiment (ChArMEx). Atmos Chem Phys. 2018;18(13):9351–73. https://doi.org/10.5194/acp-18-9351-2018.
28.• Rieder HE, Fiore AM, Clifton OE, Correa G, Horowitz LW, Naik V. Combining model projections with site-level observations to estimate changes in distributions and seasonality of ozone in surface air over the USA. Atmos Environ. 2018;193:302–15. https://doi.org/10.1016/j.atmosenv.2018.07.042. **This article used a statistical model to combine model projections and site-level observations to estimate the impacts of climate warming on surface ozone over the U.S.**
29.• Yahya K, Campbell P, Zhang Y. Decadal application of WRF/chem for regional air quality and climate modeling over the US under the representative concentration pathways scenarios. Part 2: current vs. future simulations. Atmos Environ. 2017;152:584–604. https://doi.org/10.1016/j.atmosenv.2016.12.028. **This study simulated the impacts of climate warming and future emission changes to global air quality at high resolution.**
30.• Meul S, Langematz U, Kroger P, Oberlander-Hayn S, Jockel P. Future changes in the stratosphere-to-troposphere ozone mass flux and the contribution from climate change and ozone recovery. Atmos Chem Phys. 2018;18(10):7721–38. https://doi.org/10.5194/acp-18-7721-2018. **This article examined the future change in stratosphere-troposphere exchange of ozone and the driver for that change.**
31.• Murray LT. Lightning NOx and impacts on air quality. Curr Pollut Rep. 2016;2(2):115–33. https://doi.org/10.1007/s40726-016-0031-7. **This review comprehensively examined the impacts of lightning NOx on ozone air quality.**
32. Yair Y. Lightning hazards to human societies in a changing climate. Environ Res Lett. 2018;13(12):13. https://doi.org/10.1088/1748-9326/aaea86.
33. Clark SK, Ward DS, Mahowald NM. Parameterization-based uncertainty in future lightning flash density. Geophys Res Lett. 2017;44(6):2893–901. https://doi.org/10.1002/2017gl073017.
34. Finney DL, Doherty RM, Wild O, Stevenson DS, MacKenzie IA, Blyth AM. A projected decrease in lightning under climate change. Nat Clim Chang. 2018;8(3):210. https://doi.org/10.1038/s41558-018-0072-6.

35. Jiang XY, Guenther A, Potosnak M, Geron C, Seco R, Karl T, et al. Isoprene emission response to drought and the impact on global atmospheric chemistry. Atmos Environ. 2018;183:69–83. https://doi.org/10.1016/j.atmosenv.2018.01.026.
36. Weaver CP, Liang XZ, Zhu J, Adams PJ, Amar P, Avise J, et al. A preliminary synthesis of modeled climate change impacts on us regional ozone concentrations. Bull Am Meteorol Soc. 2009;90(12):1843–63. https://doi.org/10.1175/2009bams2568.1.
37. Tai APK, Mickley LJ, Heald CL, Wu SL. Effect of CO2 inhibition on biogenic isoprene emission: implications for air quality under 2000 to 2050 changes in climate, vegetation, and land use. Geophys Res Lett. 2013;40(13):3479–83. https://doi.org/10.1002/grl.50650.
38.• Fu Y, Liao H. Biogenic isoprene emissions over China: sensitivity to the CO_2 inhibition effect. Atmospheric and Oceanic Science Letters. 2016;9(4):277–84. **This article examined the effects of three different parameterizations of CO2 inhibition to biogenic isoprene emissions.**
39.• Hantson S, Knorr W, Schurgers G, TAM P, Arneth A. Global isoprene and monoterpene emissions under changing climate, vegetation, CO2 and land use. Atmos Environ. 2017;155:35–45. https://doi.org/10.1016/j.atmosenv.2017.02.010. **This article exmined the global isoprene and monoterpene emissions between 1901 to 2100, including the effects of many land, ecosystem, and climate feedbacks.**
40. Hollaway MJ, Arnold SR, Collins WJ, Folberth G, Rap A. Sensitivity of midnineteenth century tropospheric ozone to atmospheric chemistry-vegetation interactions. J Geophys Res-Atmos. 2017;122(4):2452–73. https://doi.org/10.1002/2016jd025462.
41. Wang B, Shuman J, Shugart HH, Lerdau MT. Biodiversity matters in feedbacks between climate change and air quality: a study using an individual-based model. Ecol Appl. 2018;28(5):1223–31. https://doi.org/10.1002/eap.1721.
42. Franz M, Simpson D, Arneth A, Zaehle S. Development and evaluation of an ozone deposition scheme for coupling to a terrestrial biosphere model. Biogeosciences. 2017;14(1):45–71. https://doi.org/10.5194/bg-14-45-2017.
43.•• Sadiq M, Tai APK, Lombardozzi D, Martin MV. Effects of ozone-vegetation coupling on surface ozone air quality via biogeochemical and meteorological feedbacks. Atmos Chem Phys. 2017;17(4):3055–66. https://doi.org/10.5194/acp-17-3055-2017. **This article examined the atmosphere-ecosystem feedbacks via BVOC emissions, ozone formation, ozone damages to leaf stomatal, and ozone dry deposition.**
44.• Arnold SR, Lombardozzi D, Lamarque JF, Richardson T, Emmons LK, Tilmes S, et al. Simulated global climate response to tropospheric ozone-induced changes in plant transpiration. Geophys Res Lett. 2018;45(23):13070–9. https://doi.org/10.1029/2018gl079938. **The article examined the global transpiration responses to tropospheric ozone.**
45.•• Lombardozzi DL, Bonan GB, Levis S, Lawrence DM. Changes in wood biomass and crop yields in response to projected CO2, O-3, nitrogen deposition, and climate. J Geophys Res-Biogeosci. 2018;123(10):3262–82. https://doi.org/10.1029/2018jg004680. **This article exmined the integrated response of vegetation mass and crop yields to CO2, ozone, nitrogen deposition, and climate change.**
46.• Yue X, Unger N. Fire air pollution reduces global terrestrial productivity. Nat Commun. 2018;9:9. https://doi.org/10.1038/s41467-018-07921-4. **This article exmined the feedback of wildfire-induced ozone and aerosol pollution to global terrestrial gross primary productivity.**
47.•• Zhou SS, APK T, Sun SH, Sadiq M, Heald CL, Geddes JA. Coupling between surface ozone and leaf area index in a chemical transport model: strength of feedback and implications for ozone air quality and vegetation health. Atmos Chem Phys. 2018;18(19):14133–48. https://doi.org/10.5194/acp-18-14133-2018. **This article implemented a ozone damage parameterization to leaf area index and evaluted the feedback between ozone pollution and vegetation health.**
48. Hayes F, Mills G, Alonso R, Gonzalez-Fernandez I, Coyle M, Grunhage L, et al. A site-specific analysis of the implications of a changing ozone profile and climate for stomatal ozone fluxes in Europe. Water Air Soil Pollut. 2019;230(1):15. https://doi.org/10.1007/s11270-018-4057-x.
49. Kavassalis SC, Murphy JG. Understanding ozone-meteorology correlations: a role for dry deposition. Geophys Res Lett. 2017;44(6):2922–31. https://doi.org/10.1002/2016gl071791.
50. Clifton OE, Fiore AM, Munger JW, Malyshev S, Horowitz LW, Shevliakova E, et al. Interannual variability in ozone removal by a temperate deciduous forest. Geophys Res Lett. 2017;44(1):542–52. https://doi.org/10.1002/2016gl070923.
51. El-Madany TS, Niklasch K, Klemm O. Stomatal and non-stomatal turbulent deposition flux of ozone to a managed peatland. Atmosphere. 2017;8(9):16. https://doi.org/10.3390/atmos8090175.
52. Horvath L, Koncz P, Moring A, Nagy Z, Pinter K, Weidinger T. An attempt to partition stomatal and non-stomatal ozone deposition parts on a short grassland. Bound-Layer Meteor. 2018;167(2):303–26. https://doi.org/10.1007/s10546-017-0310-x.
53. Fuhrer J, Martin MV, Mills G, Heald CL, Harmens H, Hayes F, et al. Current and future ozone risks to global terrestrial biodiversity and ecosystem processes. Ecol Evol. 2016;6(24):8785–99. https://doi.org/10.1002/ece3.2568.
54. Hudman RC, Moore NE, Mebust AK, Martin RV, Russell AR, Valin LC, et al. Steps towards a mechanistic model of global soil nitric oxide emissions: implementation and space based-constraints. Atmos Chem Phys. 2012;12(16):7779–95. https://doi.org/10.5194/acp-12-7779-2012.
55.• Romer PS, Duffey KC, Wooldridge PJ, Edgerton E, Baumann K, Feiner PA, et al. Effects of temperature-dependent NOx emissions on continental ozone production. Atmos Chem Phys. 2018;18(4):2601–14. https://doi.org/10.5194/acp-18-2601-2018. **This study compared measurements and model to assess of the contribution of the temperature sensitivity of soil NOx emission on the ozone-temperature correlation.**
56. Yienger JJ, Levy IH. Empirical model of global soil-biogenic NOχ emissions. J Geophys Res-Atmos. 1995;100(D6):11447–64. https://doi.org/10.1029/95JD00370.
57. Vinken GCM, Boersma KF, Maasakkers JD, Adon M, Martin RV. Worldwide biogenic soil NOx emissions inferred from OMI NO2 observations. Atmos Chem Phys. 2014;14(18):10363–81. https://doi.org/10.5194/acp-14-10363-2014.
58. Voulgarakis A, Field RD. Fire influences on atmospheric composition, air quality and climate. Curr Pollut Rep. 2015;1(2):70–81. https://doi.org/10.1007/s40726-015-0007-z.
59.• Lin MY, Horowitz LW, Payton R, Fiore AM, Tonnesen G. US surface ozone trends and extremes from 1980 to 2014: quantifying the roles of rising Asian emissions, domestic controls, wildfires, and climate. Atmos Chem Phys. 2017;17(4):2943–70. https://doi.org/10.5194/acp-17-2943-2017. **This study simulated the response of U.S. surface ozone to domestic and foreign pollutant emission changes, wildifires, and climate changes between 1980 to 2014.**
60.•• Abatzoglou JT, Williams AP, Barbero R. Global emergence of anthropogenic climate change in fire weather indices. Geophys Res Lett. 2019;46(1):326–36. https://doi.org/10.1029/2018gl080959. **This study analyzed 17 climate models to evluate the future change in fire weather over different regions of the world.**
61. Buotte PC, Levis S, Law BE, Hudiburg TW, Rupp DE, Kent JJ. Near-future forest vulnerability to drought and fire varies across

the western United States. Glob Chang Biol. 2019;25(1):290–303. https://doi.org/10.1111/gcb.14490.
62. Hantson S, Arneth A, Harrison SP, Kelley DI, Prentice IC, Rabin SS, et al. The status and challenge of global fire modelling. Biogeosciences. 2016;13(11):3359–75. https://doi.org/10.5194/bg-13-3359-2016.
63. Abatzoglou JT, Williams AP. Impact of anthropogenic climate change on wildfire across western US forests. Proc Natl Acad Sci U S A. 2016;113(42):11770–5. https://doi.org/10.1073/pnas.1607171113.
64. Abatzoglou JT, Kolden CA, Williams AP, Lutz JA, Smith AMS. Climatic influences on interannual variability in regional burn severity across western US forests. Int J Wildland Fire. 2017;26(4):269–75. https://doi.org/10.1071/wf16165.
65. van Marle MJE, Kloster S, Magi BI, Marlon JR, Daniau AL, Field RD, et al. Historic global biomass burning emissions for CMIP6 (BB4CMIP) based on merging satellite observations with proxies and fire models (1750-2015). Geosci Model Dev. 2017;10(9):3329–57. https://doi.org/10.5194/gmd-10-3329-2017.
66. Li F, Lawrence DM, Bond-Lamberty B. Impact of fire on global land surface air temperature and energy budget for the 20th century due to changes within ecosystems. Environ Res Lett. 2017;12(4):10. https://doi.org/10.1088/1748-9326/aa6685.
67. Rabin SS, Melton JR, Lasslop G, Bachelet D, Forrest M, Hantson S, et al. The Fire Modeling Intercomparison Project (FireMIP), phase 1: experimental and analytical protocols with detailed model descriptions. Geosci Model Dev. 2017;10(3):1175–97. https://doi.org/10.5194/gmd-10-1175-2017.
68. Squire OJ, Archibald AT, Griffiths PT, Jenkin ME, Smith D, Pyle JA. Influence of isoprene chemical mechanism on modelled changes in tropospheric ozone due to climate and land use over the 21st century. Atmos Chem Phys. 2015;15(9):5123–43. https://doi.org/10.5194/acp-15-5123-2015.
69. Mao JQ, Carlton A, Cohen RC, Brune WH, Brown SS, Wolfe GM, et al. Southeast atmosphere studies: learning from model-observation syntheses. Atmos Chem Phys. 2018;18(4):2615–51. https://doi.org/10.5194/acp-18-2615-2018.
70. Wennberg PO, Bates KH, Crounse JD, Dodson LG, McVay RC, Mertens LA, et al. Gas-phase reactions of isoprene and its major oxidation products. Chem Rev. 2018;118(7):3337–90. https://doi.org/10.1021/acs.chemrev.7b00439.
71. Coates J, Mar KA, Ojha N, Butler TM. The influence of temperature on ozone production under varying NOx conditions - a modelling study. Atmos Chem Phys. 2016;16(18):11601–15. https://doi.org/10.5194/acp-16-11601-2016.
72. Ito A, Sillman S, Penner JE. Global chemical transport model study of ozone response to changes in chemical kinetics and biogenic volatile organic compounds emissions due to increasing temperatures: sensitivities to isoprene nitrate chemistry and grid resolution. J Geophys Res-Atmos. 2009;114:19. https://doi.org/10.1029/2008jd011254.
73. Yu KR, Jacob DJ, Fisher JA, Kim PS, Marais EA, Miller CC, et al. Sensitivity to grid resolution in the ability of a chemical transport model to simulate observed oxidant chemistry under high-isoprene conditions. Atmos Chem Phys. 2016;16(7):4369–78. https://doi.org/10.5194/acp-16-4369-2016.
74.•• Fu TM, Zheng YQ, Paulot F, Mao JQ, Yantosca RM. Positive but variable sensitivity of august surface ozone to large-scale warming in the Southeast United States. Nat Clim Chang. 2015;5(5):454–8. https://doi.org/10.1038/nclimate2567. **This study combined surface measurements and sensitivity simulations to show that surface ozone increases with large-scale warming over Southeast U.S.**
75.•• Oswald EM, Dupigny-Giroux LA, Leibensperger EM, Poirot R, Merrell J. Climate controls on air quality in the northeastern US: an examination of summertime ozone statistics during 1993-2012. Atmos Environ. 2015;112:278–88. https://doi.org/10.1016/j.atmosenv.2015.04.019. **This statistical analysis found that present day summertime ozone over the Northeastern U.S. was only weakly correlated with the number of stagnation events and the number of stagnation events.**
76.•• Porter WC, Heald CL, Cooley D, Russell B. Investigating the observed sensitivities of air-quality extremes to meteorological drivers via quantile regression. Atmos Chem Phys. 2015;15(18):10349–66. https://doi.org/10.5194/acp-15-10349-2015. **This statistical analysis showed that the ozone-temperature sensitivity over the U.S. are larger at higher ozone quantiles.**
77.•• Otero N, Sillmann J, Schnell JL, Rust HW, Butler T. Synoptic and meteorological drivers of extreme ozone concentrations over Europe. Environ Res Lett. 2016;11(2):024005. https://doi.org/10.1088/1748-9326/11/2/024005. **The article examined the meteorological drivers of extreme ozone pollution over Europe.**
78.• Jing P, Lu Z, Steiner AL. The ozone-climate penalty in the Midwestern U.S. Atmos Environ. 2017;170:130–42. https://doi.org/10.1016/j.atmosenv.2017.09.038. **This article used observations to quantify the ozone-temperature sensitivity on synoptic scales and identified the weather pattern drivers.**
79. Wang Y, Xie Y, Dong W, Ming Y, Wang J, Shen L. Adverse effects of increasing drought on air quality via natural processes. Atmos Chem Phys. 2017;17(20):12827–43. https://doi.org/10.5194/acp-17-12827-2017.
80. Zhang H, Wang YH, Park TW, Deng Y. Quantifying the relationship between extreme air pollution events and extreme weather events. Atmos Res. 2017;188:64–79. https://doi.org/10.1016/j.atmosres.2016.11.010.
81. Pope RJ, Butt EW, Chipperfield MP, Doherty RM, Fenech S, Schmidt A, et al. The impact of synoptic weather on UK surface ozone and implications for premature mortality. Environ Res Lett. 2016;11(12):10. https://doi.org/10.1088/1748-9326/11/12/124004.
82. Shu L, Xie M, Wang TJ, Gao D, Chen PL, Han Y, et al. Integrated studies of a regional ozone pollution synthetically affected by subtropical high and typhoon system in the Yangtze River Delta region, China. Atmos Chem Phys. 2016;16(24):15801–19. https://doi.org/10.5194/acp-16-15801-2016.
83. Carro-Calvo L, Ordonez C, Garcia-Herrera R, Schnell JL. Spatial clustering and meteorological drivers of summer ozone in Europe. Atmos Environ. 2017;167:496–510. https://doi.org/10.1016/j.atmosenv.2017.08.050.
84. Ordonez C, Barriopedro D, Garcia-Herrera R, Sousa PM, Schnell JL. Regional responses of surface ozone in Europe to the location of high-latitude blocks and subtropical ridges. Atmos Chem Phys. 2017;17(4):3111–31. https://doi.org/10.5194/acp-17-3111-2017.
85. Lam YF, Cheung HM, Ying CC. Impact of tropical cyclone track change on regional air quality. Sci Total Environ. 2018;610:1347–55. https://doi.org/10.1016/j.scitotenv.2017.08.100.
86.• Shen L, Mickley LJ, APK T. Influence of synoptic patterns on surface ozone variability over the eastern United States from 1980 to 2012. Atmos Chem Phys. 2015;15(19):10925–38. https://doi.org/10.5194/acp-15-10925-2015. **This article identified the synoptic weather patterns affecting surface ozone variability over eastern U.S.**
87.• Wang YX, Jia BX, Wang SC, Estes M, Shen L, Xie YY. Influence of the Bermuda high on interannual variability of summertime ozone in the Houston-Galveston-Brazoria region. Atmos Chem Phys. 2016;16(23):15265–76. https://doi.org/10.5194/acp-16-15265-2016. **This article quantified the impacts of the interannual variability of the Bermuda High on summertime ozone over southern Texas.**
88.• Schnell JL, Prather MJ. Co-occurrence of extremes in surface ozone, particulate matter, and temperature over eastern North

America. Proc Natl Acad Sci. 2017;114(11):2854. https://doi.org/10.1073/pnas.1614453114. **The article examined the spatial and temperal features of co-occurring high ozone, PM2.5 and temperature under present and future climate.**

89. Garrido-Perez JM, Ordonez C, Garcia-Herrera R, Barriopedro D. Air stagnation in Europe: spatiotemporal variability and impact on air quality. Sci Total Environ. 2018;645:1238–52. https://doi.org/10.1016/j.scitotenv.2018.07.238.
90. Seo J, Park DSR, Kim JY, Youn D, Lim YB, Kim Y. Effects of meteorology and emissions on urban air quality: a quantitative statistical approach to long-term records (1999-2016) in Seoul, South Korea. Atmos Chem Phys. 2018;18(21):16121–37. https://doi.org/10.5194/acp-18-16121-2018.
91. Horton DE, Skinner CB, Singh D, Diffenbaugh NS. Occurrence and persistence of future atmospheric stagnation events. Nat Clim Chang. 2014;4:698. https://doi.org/10.1038/nclimate2272.
92. Caserini S, Giani P, Cacciamani C, Ozgen S, Lonati G. Influence of climate change on the frequency of daytime temperature inversions and stagnation events in the Po Valley: historical trend and future projections. Atmos Res. 2017;184:15–23. https://doi.org/10.1016/j.atmosres.2016.09.018.
93.• Hou P, Wu SL. Long-term changes in extreme air pollution meteorology and the implications for air quality. Sci Rep. 2016;6:9. https://doi.org/10.1038/srep23792. **This statistical analyses found increasing trends of extreme air pollution meteorological events over continental regions of the world during the past six decades, as well as strong sensitivities of air pollutant concentrations to those events.**
94.•• Sun W, Hess P, Liu C. The impact of meteorological persistence on the distribution and extremes of ozone. Geophys Res Lett. 2017;44(3):1545–1553. https://doi.org/10.1002/2016GL071731. **This statistical analyses found that persistent high temperature (i.e., heat waves) does not result in further ozone increases in any region over the U.S.**
95. Kerr GH, Waugh DW. Connections between summer air pollution and stagnation. Environ Res Lett. 2018;13(8):10. https://doi.org/10.1088/1748-9326/aad2e2.
96. Pu X, Wang TJ, Huang X, Melas D, Zanis P, Papanastasiou DK, et al. Enhanced surface ozone during the heat wave of 2013 in Yangtze River Delta region, China. Sci Total Environ. 2017;603:807–16. https://doi.org/10.1016/j.scitotenv.2017.03.056.
97. Pyrgou A, Hadjinicolaou P, Santamouris M. Enhanced near-surface ozone under heatwave conditions in a Mediterranean island. Sci Rep. 2018;8:10. https://doi.org/10.1038/s41598-018-27590-z.
98.•• Zhang JX, Gao Y, Luo K, Leung LR, Zhang Y, Wang K, et al. Impacts of compound extreme weather events on ozone in the present and future. Atmos Chem Phys. 2018;18(13):9861–77. https://doi.org/10.5194/acp-18-9861-2018. **This modeling study examined the impacts of heat waves, atmospheric stagnation, and their compound occurrence on surface ozone under present and future climate.**
99. Meehl GA, Tebaldi C, Tilmes S, Lamarque JF, Bates S, Pendergrass A, et al. Future heat waves and surface ozone. Environ Res Lett. 2018;13(6):9. https://doi.org/10.1088/1748-9326/aabcdc.
100. Phalitnonkiat P, Hess PGM, Grigoriu MD, Samorodnitsky G, Sun WX, Beaudry E, et al. Extremal dependence between temperature and ozone over the continental US. Atmos Chem Phys. 2018;18(16):11927–48. https://doi.org/10.5194/acp-18-11927-2018.
101. Steiner AL, Davis AJ, Sillman S, Owen RC, Michalak AM, Fiore AM. Observed suppression of ozone formation at extremely high temperatures due to chemical and biophysical feedbacks. Proc Natl Acad Sci U S A. 2010;107(46):19685–90. https://doi.org/10.1073/pnas.1008336107.
102.•• Zhang YZ, Wang YH. Climate-driven ground-level ozone extreme in the fall over the Southeast United States. Proc Natl Acad Sci U S A. 2016;113(36):10025–30. https://doi.org/10.1073/pnas.1602563113. **This study proposed that a drying and warming fall under future climate will lengthen the regional ozone pollution season over Southeast U.S.**
103.• Shen L, Mickley LJ, Leibensperger EM, Li MW. Strong dependence of US summertime air quality on the decadal variability of Atlantic Sea surface temperatures. Geophys Res Lett 2017;44(24):12527–12535. https://doi.org/10.1002/2017gl075905. **This article examined the impacts of the phase of the Atlanic Multidecadal Oscillation on US summertime air quality.**
104. Marlier ME, DeFries RS, Voulgarakis A, Kinney PL, Randerson JT, Shindell DT, et al. El Nino and health risks from landscape fire emissions in Southeast Asia. Nat Clim Chang. 2013;3(2):131–6. https://doi.org/10.1038/nclimate1658.
105. Yi K, Liu JF, Ban-Weiss G, Zhang JC, Tao W, Cheng YL, et al. Response of the global surface ozone distribution to Northern Hemisphere sea surface temperature changes: implications for long-range transport. Atmos Chem Phys. 2017;17(14):8771–88. https://doi.org/10.5194/acp-17-8771-2017.
106. Lin MY, Fiore AM, Horowitz LW, Langford AO, Oltmans SJ, Tarasick D, et al. Climate variability modulates western US ozone air quality in spring via deep stratospheric intrusions. Nat Commun. 2015;6:11. https://doi.org/10.1038/ncomms8105.
107. Olsen MA, Wargan K, Pawson S. Tropospheric column ozone response to ENSO in GEOS-5 assimilation of OMI and MLS ozone data. Atmos Chem Phys. 2016;16(11):7091–103. https://doi.org/10.5194/acp-16-7091-2016.
108.•• Barnes EA, Fiore AM, Horowitz LW. Detection of trends in surface ozone in the presence of climate variability. J Geophys Res-Atmos. 2016;121(10):6112–29. https://doi.org/10.1002/2015jd024397. **This article showed that regional surface ozone may be strongly influenced by natural climate variability in the near-term, such that anthropogenic GHG-forced trends in ozone may be difficult to detect robustly until the later half of the 21st century.**
109.•• Garcia-Menendez F, Monier E, Selin NE. The role of natural variability in projections of climate change impacts on US ozone pollution. Geophys Res Lett. 2017;44(6):2911–21. https://doi.org/10.1002/2016gl071565. **This article showed that a minimum 15-year simulation is required to smooth out the noise on surface ozone induced by natural climate variability.**
110. Balashov NV, Thompson AM, Piketh SJ, Langerman KE. Surface ozone variability and trends over the South African Highveld from 1990 to 2007. J Geophys Res-Atmos. 2014;119(7):4323–42. https://doi.org/10.1002/2013jd020555.
111.• Fann N, Nolte CG, Dolwick P, Spero TL, Brown AC, Phillips S, et al. The geographic distribution and economic value of climate change-related ozone health impacts in the United States in 2030. J Air Waste Manage Assoc. 2015;65(5):570–80. https://doi.org/10.1080/10962247.2014.996270. **This article evaluated the effects of future climate change on ozone and its health impacts in the U.S.**
112.• Gonzalez-Abraham R, Chung SH, Avise J, Lamb B, Salathé EP Jr, Nolte CG, et al. The effects of global change upon United States air quality. Atmos Chem Phys. 2015;15(21):12645–65. https://doi.org/10.5194/acp-15-12645-2015. **This article examined the individual and combined effects of future changes in climate, land use, emissions, and long range transports on U.S. air quality.**
113.• Val Martin M, Heald CL, Lamarque JF, Tilmes S, Emmons LK, Schichtel BA. How emissions, climate, and land use change will impact mid-century air quality over the United States:a focus on effects at national parks. Atmos Chem Phys. 2015;15(5):2805–23. https://doi.org/10.5194/acp-15-2805-2015. **This article**

examined the individual and combined effects of future changes in climate, land use, and emissions on air quality at U.S. national parks.

114.• He H, Liang XZ, Lei H, Wuebbles DJ. Future US ozone projections dependence on regional emissions, climate change, long-range transport and differences in modeling design. Atmos Environ. 2016;128:124–33. https://doi.org/10.1016/j.atmosenv.2015.12.064. **This study evaluated the differences in projected U.S. ozone due to changes in emissions, climate, long-range transport, and modeling designs.**

115.• Nolte CG, Spero TL, Bowden JH, Mallard MS, Dolwick PD. The potential effects of climate change on air quality across the conterminous US at 2030 under three representative concentration pathways. Atmos Chem Phys. 2018;18(20):15471–89. https://doi.org/10.5194/acp-18-15471-2018. **This article projected U.S. ozone air quality under three future climate and emission scenarios.**

116.• Rieder HE, Fiore AM, Horowitz LW, Naik V. Projecting policy-relevant metrics for high summertime ozone pollution events over the eastern United States due to climate and emission changes during the 21st century. J Geophys Res-Atmos. 2015;120(2):784–800. https://doi.org/10.1002/2014jd022303. **This article projected U.S. summertime ozone due to climate and emission changes during the 21st century.**

117.• Lee JB, Cha JS, Hong SC, Choi JY, Myoung JS, Park RJ, et al. Projections of summertime ozone concentration over East Asia under multiple IPCC SRES emission scenarios. Atmos Environ. 2015;106:335–46. https://doi.org/10.1016/j.atmosenv.2015.02.019. **This article evaluated the impacts of future climate and emission changes on summertime ozone over East Asia.**

118.• Pommier M, Fagerli H, Gauss M, Simpson D, Sharma S, Sinha V, et al. Impact of regional climate change and future emission scenarios on surface O-3 and PM2.5 over India. Atmos Chem Phys. 2018;18(1):103–27. https://doi.org/10.5194/acp-18-103-2018. **This article evaluated the impacts of future climate and emission changes on air quality over India.**

119.•• Schnell JL, Prather MJ, Josse B, Naik V, Horowitz LW, Zeng G, et al. Effect of climate change on surface ozone over North America, Europe, and East Asia. Geophys Res Lett. 2016;43(7):3509–18. https://doi.org/10.1002/2016gl068060. **This article compared the results from four global climate-chemistry models to assess the impacts of climate change on surface ozone over North America, Europe, and East Asia.**

120. Colette A, Andersson C, Baklanov A, Bessagnet B, Brandt J, Christensen JH, et al. Is the ozone climate penalty robust in Europe? Environ Res Lett. 2015;10(8):9. https://doi.org/10.1088/1748-9326/10/8/084015.

121. Guo JJ, Fiore AM, Murray LT, Jaffe DA, Schnell JL, Moore CT, et al. Average versus high surface ozone levels over the continental USA: model bias, background influences, and interannual variability. Atmos Chem Phys. 2018;18(16):12123–40. https://doi.org/10.5194/acp-18-12123-2018.