Meteorology and Climate Influences on Tropospheric Ozone: a Review of Natural Sources, Chemistry, and Transport Patterns

Xiao Lu^{1,2} · Lin Zhang¹ · Lu Shen²

Published online: 12 July 2019

© The Author(s) 2019

Abstract

Tropospheric ozone is a key air pollutant and greenhouse gas. Its fate strongly depends on meteorological conditions and therefore subject to climate change influences. Such dependences through biogenic, chemical, and dynamic processes on different spatiotemporal scales have been unraveled from observations and modeling studies. In this process-oriented review, we summarize three dominant pathways of meteorological and climatic impacts on tropospheric ozone and present their recent progress. The three pathways are influences through changes in the natural precursor emissions, the kinetics and partitioning of chemistry and deposition, and the transport of ozone and its precursors. Tropospheric ozone levels have shown significant global or regional responses to meteorological/climatic changes (e.g., changes in the Brewer-Dobson Circulation, the Hadley Circulation, and El Niño–Southern Oscillation) and can be explained through the conjunction of these pathways. Most recent model projections predict that future climate will increase surface ozone in polluted regions and decrease ozone at a global scale due to stronger ozone chemical loss. However, uncertainties in climate-ozone responses and limitations in model capability still challenge the magnitude and even the sign of such projections. We highlight the rising importance of future increase of stratosphere-troposphere exchange in modulating tropospheric ozone that may largely compensate the predicted chemical loss of tropospheric ozone burden. We also highlight that uncertainties in isoprene chemistry, biogenic emissions in changing CO₂ levels and vegetation, and interactions between ozone and vegetation may largely affect the surface ozone response to climate change. Future research and model improvements are required to fill these gaps.

Keywords Tropospheric ozone · Ozone · Meteorology · Climate · Natural sources

Introduction

Ozone at the surface is detrimental to human health and ecosystem [123], while in the middle and upper troposphere, it is a greenhouse gas contributing to positive radiative forcing [175, 184]. Efforts of reducing anthropogenic emissions of ozone precursors such as nitrogen oxides (NO_x = NO + NO₂) have been applied to improve ozone air quality particularly in

Europe and North America [51]. However, as the natural sources, chemistry, and transport of ozone and its precursors are highly climate-sensitive, the effectiveness of such efforts will be modulated by climate variations or even offset by unfavorable weather conditions, imposing challenges for ozone quality management. As such, it is of particular importance to evaluate the connections between tropospheric ozone and meteorological conditions (and associated climate variations), and their implications for future ozone projection in the context of climate change. We review our current understandings and recent advances on this issue.

Meteorology variations and climate change influence tropospheric ozone through a number of processes. We summarize three dominant pathways in Fig. 1, including (1) natural emission pathway, i.e., a large amount of ozone precursors are emitted from climate-sensitive natural sources such as lightning and biosphere; (2) chemistry pathway, i.e., meteorological conditions such as solar radiation, temperature, and humidity alter the partitioning and efficiency of chemical reactions

This article is part of the Topical Collection on *Air Pollution*

✉ Lin Zhang
zhanglg@pku.edu.cn

¹ Laboratory for Climate and Ocean-Atmosphere Studies, Department of Atmospheric and Oceanic Sciences, School of Physics, Peking University, Beijing 100871, China

² School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA

Fig. 1 Pathways of interaction between meteorology/climate changes and tropospheric ozone. The red (blue) triangles represent that at global scale future climate will increase (decrease) tropospheric ozone through

the specific pathway based on current understanding. More discussions are provided in the text

and dry deposition, and therefore modulate ozone production and loss; and (3) transport pathway, as the lifetime of ozone and its precursors in the free troposphere can be longer than months, they are subject to changes of transport patterns on different spatiotemporal scales. It shall be noted that the impacts of meteorology and climate on tropospheric ozone often appear as a conjunction of more than one pathway. Tropospheric ozone changes in turn alter climate through radiative feedback and interactions with the biosphere (Fig. 1).

The overall responses of tropospheric ozone to changes of meteorology and climate have been summarized in previous reviews [46, 47, 78, 82, 205]. The responses are generally quantified through observed statistical relationships of ozone with meteorological variables, or through perturbation analyses using chemical models [82]. One distinguished finding is the positive surface ozone-temperature relationship in the polluted regions, mainly driven by the role of temperature in increasing natural emissions (in particular biogenic isoprene emissions) and accelerating ozone chemical production at high NO_x levels [150]. The positive ozone-temperature relationship implies that global warming will deteriorate surface ozone air quality in industrial regions even without increases of anthropogenic emission, an impact referred as “climate penalty” [217]. Previous reviews also documented the relationship between ventilation conditions (stagnations and cyclones) and ozone air quality, and summarized future ozone projections driven by climate change, although the confidence of such projections can be limited by uncertainties in chemical mechanisms (such as organic nitrates production) and the lack of atmosphere-biosphere interactions in the model [46].

Different from previous reviews which focus on the overall ozone response to climate change, this study aims to present a process-oriented review on how meteorology and tropospheric ozone interacts through each of the pathways. A number of recent progresses of these processes are also included. Particularly, recent studies have shown that shifts of stratosphere-troposphere exchange (STE) and large-scale climate patterns such as the El Niño–Southern Oscillation (ENSO) and Atlantic Multidecadal Oscillation (AMO) have significant impacts on present-day ozone distribution and future ozone projections. We include these important responses in the review. The review is organized as follows. The three pathways as described in Fig. 1 are reviewed in the “Effect on Natural Sources of Ozone Precursors” section, the “Effect on Ozone Chemistry and Deposition” section, and the “Effect on Ozone and Precursor Transport Patterns (Associated with Weather and Climate Patterns)” section, respectively. We summarize recent studies (since 2009) of future tropospheric ozone projections due to climate change in the “Future Ozone Change Due to Climate Change” section, and discuss the feedback from tropospheric ozone to climate in the “Feedback from Tropospheric Ozone Change to Climate” section. A conclusion is provided in the “Conclusion” section.

Effect on Natural Sources of Ozone Precursors

We start with a brief overview on tropospheric ozone chemistry summarized from Jacob [81], Atkinson [7], and Wang et al.

[210]. In the troposphere, photolysis of NO_2 (at wavelengths < 424 nm) provides $\text{O}(^3\text{P})$ (the ground electronic state oxygen atom) (1). Ozone is then formed through a termolecular reaction of $\text{O}(^3\text{P})$, O_2 , and a third body M (2).

O_3 reacts rapidly with NO to regenerate NO_2 through (3),

contributing to null ozone production through (1)–(3). However, the presence of oxidant radicals (hydroperoxyl radical (HO_2) and organic peroxy radicals (RO_2)) provides additional pathways to convert NO to NO_2 through (4) and (5),

RO_2 , HO_2 are products from oxidation of CO (6), hydrocarbons (RH, 7), or alkoxy radicals (RO) (8).

The oxidation of CO and hydrocarbons requires hydroxyl radical (OH). It originates principally from photolysis of O_3 (9) and reaction with water vapor (10).

The above mechanisms present the tropospheric ozone production through a chain photochemical oxidations of CO and hydrocarbons (or in broader context, volatile organic compounds (VOCs)) catalyzed by HO_x ($\text{HO}_x = \text{OH} + \text{H} + \text{peroxy radicals}$) in the presence of NO_x . The chain is terminated by the loss of HO_x radicals, which happens through the oxidation of NO_2 by OH (11), and the self-reaction of HO_2 (12):

H_2O_2 and HNO_3 are then removed mainly by wet deposition due to their high solubility in water.

Ozone chemistry is strongly nonlinear. At low NO_x levels, the controlling termination is (12); thus, ozone production is limited by the supply of NO_x and is not sensitive to hydrocarbons, referred as “ NO_x -limited regime.” At high NO_x levels, the controlling termination is (11); thus, ozone production linearly increases with VOCs concentrations but decreases with NO_x concentrations, referred as “VOC-limited regime.”

Meteorological conditions therefore influence ozone through modulating the climate-sensitive natural emission of its precursors, including soil NO_x emissions (“Soil NO_x Emission” section), lightning NO_x emissions (“Lightning NO_x Emission” section), biogenic VOC (BVOC) emissions (“BVOC Emissions” section), wildfire emissions (“Wildfire Emission” section), and wetland methane emissions (“Wetland Methane Emissions” section). We present a process-based description on the role of meteorology in each process and discuss the ozone response.

Soil NO_x Emission

NO_x can be produced naturally from soil as byproduct of microbial activities (nitrification and denitrification). Soil emissions contribute to approximately 10–15% (3 to 8 Tg N year^{−1}) of the present-day global NO_x emissions ([31, 77, 196, 204]). It is controlled by inorganic nitrogen availability in soil, canopy structure (such as vegetation type), and edaphic conditions such as soil temperature and moisture [204, 226].

Soil temperature and moisture are critical factors in controlling soil NO_x emissions. These two factors together can explain up to 74% of the observed variations of soil NO_x emissions in European forests [160]. Rising soil temperature accelerates the enzymatic process and exponentially increases soil emissions as observed over different biomes [160, 222]. The dependence of soil emissions on temperature, however, weakens when soil temperature further increases (e.g., above 30 °C) and soil becomes dry, and then soil emissions become more limited by water content [222]. High soil moisture also suppresses soil NO_x emissions, as wet condition with fewer oxygen supply favors denitrification which preferentially emits N_2O and N_2 , and also limits gas diffusion through the soil pores [77, 222]. Further impacts from soil moisture can be found when there is a sudden shift from dry to wet conditions. The sudden shift can release accumulated inorganic N rapidly and reactivate the water-stressed bacteria, leading to a burst of soil NO_x emission. Rapid and intense soil NO_x pulsing emissions following rainfall in the US and India have been captured by daily satellite NO_2 observations [13, 53].

Changes in soil NO_x emissions due to variations of meteorology and climate further modulate ozone. As soil emissions dominate in rural regions where ozone chemical production is typically NO_x -limited, it is expected that soil NO_x emissions trigger strong local ozone production. Romer et al. [152] showed that soil NO_x emissions contributed to nearly half of the ozone increases with rising temperature in a rural site in the southeastern US. Hudman et al. [76] showed that warmer (2 K) and drier (50%) weather conditions followed by convective precipitation over the central US in June 2006 led to about 50% higher soil NO_x emissions compared to the average for 2005–2008, mainly due to stronger pulsing emissions in

that year. Increased soil NO_x emissions alone then led to surface ozone enhanced by 3–5 ppbv (episodically up to 16 ppbv). Similar enhancements (May–August 2017 vs. 2016) of soil NO_x emissions (~25%) and surface ozone (1–2 ppbv) due to warmer climate were simulated over the industrial eastern China [119]. For future projections, modeling studies predict significant enhancement of soil NO_x emissions driven by climate change (e.g., ~23% higher in 2100 compared to 2000 in IPCC A2 emission scenario, [61, 108]), underlying future climate will likely degrade ozone air quality via increasing soil NO_x emissions.

Lightning NO_x Emission

Energy produced by lightning flashes dissociates and converts atmospheric N₂ molecules into NO_x. Estimated global lightning NO_x emissions are ranging from 2 to 8 Tg a⁻¹ N with large uncertainties [31, 126, 163]. The importance of lightning NO_x in atmospheric chemistry and potential radiative effect is disproportionally large as it is mainly released in the upper troposphere, where ozone chemical production is more efficient, and where NO_x and ozone have longer lifetimes [10].

Lightning NO_x emissions strongly depend on the intensity and frequency of lightning activities in the convective thunderstorms. Price and Rind [149] showed that the total lightning flash frequency in the thunderstorm exponentially increased with convective cloud top height (CTH) with a power of 4.9 in continental cloud. Several studies also linked lightning flashes to other convection-related characters such as updraft velocity, latent heat release, and more recently upward cloud ice flux [40, 42, 163]. These dependencies are then parameterized into models to estimate lightning NO_x emission and ozone production. Lightning emissions contribute to upper tropospheric ozone by more than 10 ppbv [27, 75], and also influence surface ozone especially at regions with high elevations such as the US Intermountain West and the Tibetan Plateau [119, 238]. It is also an important driver of observed interannual variability of ozone and OH in tropical upper troposphere [125, 127].

Climate variabilities can then influence tropospheric ozone through altering lightning NO_x emissions. Anomalously, high ozone contributed by lightning emissions in El Niño conditions (“Large-Scale Climate Patterns (ENSO, AMO, NAO)” section) has been found at tropical upper-troposphere [55, 130] due to intensified convection over land and coastal area [58]. The projected changes of future lightning ozone productions due to climate change, however, largely depend on the parameterization of lightning in the model. Most studies with lightning parameterized based on CTH showed enhancements of lightning NO_x emissions (4–60% K⁻¹) in the warming future due to more frequent and intense convections [163]. However, studies that used cloud ice flux for parameterization resulted in an opposite conclusion, as the cloud ice crystal

declines with increasing temperature [41, 42, 83]. Therefore, the projections of future lightning and its impact on ozone need to be interpreted with caution.

BVOC Emissions

VOCs are important ozone precursors, a large amount of which are emitted from terrestrial ecosystems. BVOC emissions vary among plant functional types and are strongly modulated by meteorological conditions. Temperature is one of the key factors controlling BVOCs emissions due to the nature of photosynthesis. Exponential enhancements of biogenic isoprene and monoterpene emissions with rising temperature have been shown in field and laboratory observations and implemented in chemical models [57]. The exponential dependency of BVOC emissions on increasing temperature is also identified as a main driver of the positive ozone-temperature correlations especially over urban areas where NO_x levels are high [119, 150]. Modeling results showed that a 3 K temperature enhancement on BVOC emissions alone would increase biogenic isoprene emissions by 6–31% and surface ozone by > 2 ppbv in the northern mid-latitudes [35]. The increased isoprene also affects the partitioning among oxidized nitrogen to produce more peroxyacetyl nitrate (PAN, a NO_x reservoir compound), which can transport a long distance and produce ozone downwind ([45]; see also the “HO_x Chemistry” section).

BVOC emissions are suppressed at extreme high temperature conditions (e.g., > 40 °C) which adversely affect cellular activities [56]. The suppression of biogenic isoprene emissions can explain the observed decline of surface ozone at extreme high temperatures (> 312 K) over California [183]. Drought conditions also impede isoprene emissions as decreasing water content slows down photosynthetic rate and stomatal conductance. Jiang et al. [87] estimated that including the drought effect in the model would lead to reduction of biogenic isoprene emissions by 17% globally. However, there is evidence that in the initial phase of drought, the shutdown of the plant physiological processes can enhance BVOC emissions [87, 144, 148]. Zhang and Wang [235] showed that enhanced biogenic isoprene emissions from water-stressed plants at the onset stage of drought contributed to the abnormally high ozone episodes over the southeast US in October 2010.

Model projections tend to predict significant increases of BVOC emissions in the warming future, which would elevate tropospheric ozone concentrations (e.g., [109, 199, 217]). However, these projections might be influenced by uncertainties in isoprene chemistry and interactions with the biosphere as pointed out by recent studies and summarized as follows:

1. Uncertainties in isoprene chemistry. Whereas oxidation of the emitted BVOCs by OH produces RO₂ (7) and further

generates NO₂ (5) and ozone, RO₂ and NO can also go through another branch that forms isoprene nitrates (RONO₂),

$$\text{NO} + \text{RO}_2 + \text{M} \rightarrow \text{RONO}_2 + \text{M} \quad (13)$$

RONO₂ presents as a sink of both NO_x and RO₂, thus inhibits ozone production. The ratio of (13) branch in the total (NO+RO₂) reaction is estimated to be 10 ± 5% [142, 219], depending on a variety of factors including temperature [7, 164]. Isoprene nitrates could be either recycled to regenerate NO₂ and ozone, or be deposited to surface [142]. Therefore, different chemical mechanisms of isoprene oxidations (whether include (13) or not, include recycle or not, and their ratios) presented in the models determine the sensitivity of ozone to perturbed temperature and biogenic isoprene emissions [49, 79, 182, 216]. Through modeling studies, Ito et al. [79] showed that if no RONO₂ were recycled to NO_x, the ozone burden would be 17 Tg higher in a 5 K warmer scenario than the cooler scenario, while if all RONO₂ were recycled, ozone burden differences between the two scenarios would be much larger (57 Tg). Fu et al. [49] also showed that assuming a higher cycling rate of RONO₂ (55% versus 0%) in the model produced a larger sensitivity of surface ozone to temperature (8 ppbv K⁻¹ vs. 5 ppbv K⁻¹ in 2000) in the southeastern US. Improving understanding of isoprene chemistry mechanism is therefore critical for estimating the climate-BVOC-ozone response.

2. Response to future ambient CO₂ concentrations. Laboratory and field observations have shown substantial reductions in isoprene synthesis at elevated ambient CO₂ levels [6]. As such, future CO₂ increases could largely offset [63, 191], or even counteract the warming induced enhancements of BVOC emissions [59]. Tai et al. [191] showed that including CO₂ inhibition on BVOC emissions in the model decreased projected future surface ozone in eastern US, Southeast Asia, and Europe by 6 ppbv compared to the results without CO₂ inhibition, but increased ozone in western Amazon, central Africa, and Southeast Asia, where reduced sequestration of NO_x by isoprene oxidation products enhanced NO_x levels in these NO_x-limited regions [228]. The above studies all point to the important role of the CO₂ inhibition effect on BVOC emissions that may change the magnitudes and signs of future ozone projections, yet most of the current projections tend to miss this mechanism in the models (see also “Future Ozone Change Due to Climate Change” section).

3. Changes in land cover/vegetation types. Future environment (e.g., higher CO₂ fertilization, changes in temperature and precipitation) could naturally alter the abundance and distribution of vegetation, which may lead to large discrepancies in the projected effect on BVOC emissions. Sanderson et al. [158] showed that the climate-driven changes of vegetation types (e.g., the recession of tropical forests) would lead to less BVOC emissions, while Wu et al. [218] found increases in

global isoprene emissions. More recently, Hantson et al. [59] found that such different responses largely depended on the relative changes of different plant functional types.

Wildfire Emission

Wildfires emit large amounts of CO, NO_x, and VOCs and produce approximately 170 Tg year⁻¹ (about 3.5% of the annual total chemical production) of ozone with large interannual variability [84]. Meteorology can alter wildfire emissions and associated ozone production through modulating (1) wildfire frequency and intensity, (2) emitted tracers, and (3) ozone photochemistry in wildfire plumes.

Wildfires are prone to occur in hot and dry weather conditions. The intensity and frequency of wildfires have been increasing in the western US since 1970 due to rising temperature and earlier snowmelt [214]. Lu et al. [116] estimated the relationship between meteorological parameters and summertime wildfire frequency and intensity at monitoring sites in the western US. They found that occurrences of large wildfire events could enhance notably with increasing temperature and solar radiation, and with decreasing relative humidity and wind speed. When temperature was higher than 30 °C, the frequency of large wildfire events was four times higher than that of small events. Wildfire emissions are also influenced by combustion efficiency, which largely depends on meteorological conditions [168]. High temperature favors flaming combustion (high combustion efficiency), leading to stronger oxidation of fuel nitrogen compounds, larger proportion of NO_x emissions, and therefore higher ozone production. Smoldering combustions in cooler conditions, on the other hand, tend to release higher proportion of reduced nitrogen compounds such as NH₃ and are not favorable for ozone production [84].

Ozone chemical production in wildfire plumes is also subject to meteorological conditions. Low temperature typically in boreal wildfires favors rapid conversion from emitted NO_x to PAN. It limits ozone production near fire burning spots but may lead to ozone enhancement downwind ([3], see also “PAN Chemistry” section). Vertical diffusion influences the injection heights of wildfire plumes which are critical to ozone production and transport [200, 246]. At higher altitudes, the wildfire plumes are exposed to higher solar radiation without the blocking of wildfire aerosols and can also be more efficiently transported downwind [86, 141]. All these complexities in meteorology-relevant wildfire emissions and chemistry lead to a wide range of observed wildfire ozone enhancements as the plumes travel and age ([84], and reference therein), and make it difficult for chemical transport models to capture wildfire ozone influences especially at coarse grid resolution [116, 238].

Hot and dry weather condition then favors wildfire ozone enhancement, as it increases the frequency and intensity of

wildfire, enhances the combustion efficiency, and facilitates wildfire ozone chemical production. Summertime wildfire ozone enhancements in the western US could be 1–3 ppbv higher in hot and dry years such as 2002–2003 than other years [116]. Predictions of future wildfire activities have been available in several climate models or vegetation models [93, 203], all suggesting increasing burned area and wildfire emissions in the warming future, consistent with previous projections based on statistical methods [19, 181, 230].

Wetland Methane Emissions

Methane is an important ozone precursor in remote regions due to its long chemical lifetime (about 9 years). Wetland emissions (100–250 Tg year⁻¹) are the dominant natural source accounting for 20–50% of the total methane emissions [92, 159]. Wetland releases methane when bacteria reduce organic carbon to methane under the anaerobic environment [15]. This process is controlled by soil temperature which influences bacteria activity, water table position which determines production and oxidation depth, carbon availability (soil carbon substrate), and decomposition rate [14, 159]. Increasing temperature accelerates the methane production and oxidation rates. Increasing precipitation extends wetland areas and raises water tables; both enhance wetland methane emissions [134]. Christensen et al. [20] showed that soil temperature explained 84% of the methane emission variations over a number of northern wetland sites. Recent studies pointed out that climate variabilities such as ENSO could partly explain the interannual variations of wetland methane emissions especially in tropics through changes in temperature and precipitation [68, 245].

Significant enhancements of wetland methane emissions are projected with future increases in temperature and precipitation [134], although the enhancements may be partly offset by the effect of soil moisture depletion [18]. Shindell et al. [174] showed that global wetland methane emissions would increase by 78% if CO₂ concentrations double in the future. Increasing wetland methane emissions would cause a cascade of chemical influences and climate feedbacks. It could enhance ozone concentration, influence global OH burden [174], amplify methane chemical lifetime, exert a strong radiative forcing that faster the warming [52], and further increase methane emissions from wetland and thawing permafrost [134].

However, so far, only few models include interactive climate-sensitive wetland methane emissions, with the majority using prescribed methane mixing ratios for the future ozone projection [99, 124]. To our knowledge, future ozone changes due to increasing wetland methane emissions have not been comprehensively quantified so far. Our current understanding of ozone production from climate-sensitive natural methane sources such as permafrost, lakes and ponds

[215], and marine methane hydrate [153] are rather limited, and should be addressed in the future studies.

Effect on Ozone Chemistry and Deposition

Meteorology can influence tropospheric ozone through modulating the rate of chemical kinetics, the partitioning of reaction pathways, and efficiency of deposition. In this session, we discuss changes in ozone production and loss due to climate-sensitive PAN chemistry (“[PAN Chemistry](#)” section), HO_x chemistry (“[HO_x Chemistry](#)” section), and dry deposition (“[Dry Deposition](#)” section).

PAN Chemistry

PAN is generated through the oxidation of acetaldehyde in the presence of NO_x in hydrocarbon-rich environment ((14) and (15)) [81].

It is removed mainly via thermal decomposition (16) in the lower troposphere below ~ 7 km [192].

One important feature of PAN is the dependence of its lifetime on temperature. Because the decomposition rate of PAN (16) drops dramatically with decreasing temperature, the lifetime of PAN extends from 30 min at 295 K to several months at 240 K [7, 81]. This feature allows temperature to influence the production and transport of ozone through PAN chemistry. The formation of PAN serves as sinks for both NO_x and peroxy radicals, and therefore lowers ozone production near the source region. Nevertheless, PAN can be transported to a long distance in the cold free troposphere, eventually be thermally decomposed to release NO_x (often due to air heating with subsidence), and consequently enhances ozone production with high efficiency in remote regions [48]. Previous studies have shown the role of PAN as a NO_x reservoir compound that helps transport NO_x from polluted regions such as east Asia [236] and fire spots [3] to remote regions and produce ozone there. Increasing PAN thermal decomposition with rising temperature is also a driver of the observed positive ozone-temperature correlation [150], but this relationship could be much weaker at extremely high temperature (e.g., > 312 K, [183]).

Temperature increases in the future will lead to stronger thermal decomposition on PAN, resulting in ozone increases in the polluted regions but decreases in remote regions. Doherty et al. [35] showed that a 3 K temperature increase

on the chemical reaction rate coefficient of (16) would cause up to 4.2 ppbv ozone enhancement over land and up to 1 ppbv ozone decrease over the remote oceans. The decrease of PAN over remote regions, however, can be compensated by increasing PAN generated from higher BVOC emissions in warmer climate as discussed in the “BVOC Emissions” section.

HO_x Chemistry

Atmospheric water vapor (HO_x sources) is essential to ozone photochemistry. Its influences on tropospheric ozone are sensitive to ozone chemical regimes. In the remote regions where NO_x levels are low, ozone removal by HO_x is effective, resulting in significant negative correlations between ozone concentration and relative humidity (as a proxy of HO_x concentration), e.g., ozone vs. relative humidity correlation of −0.69 in the summertime western US in 1989–2010 [116]. In polluted regions where NO_x levels are relatively high, water vapor has competing effects on ozone production. OH radical oxidizes CO and hydrocarbons through (4)–(8) and activates ozone production, while it also terminates ozone formation by converting NO₂ to nitric acid (HNO₃) (11), leading to a more complicated relationship between ozone and water vapor [82]. These weak or sign-varied correlations have been revealed in urban areas in Europe and the US [9, 17].

From a global perspective, increasing water vapor in the warming future would lead to a decline of tropospheric ozone burden [205]. Doherty et al. [35] showed that 19% increase of water vapor would reduce surface mean ozone concentrations by 1–2 ppbv for global average and 3 ppbv in the tropics. In the US, however, Dawson et al. [29] showed that 20% decrease of absolute humidity would reduce the national mean surface ozone by 0.5 ppbv. A positive response of ozone to increasing water vapor content was also found in California in a recent study [69], reflecting the competing role of water vapor in tropospheric ozone in polluted regions.

Dry Deposition

Dry deposition to vegetation is an important sink of tropospheric ozone, accounting for about 20% of the annual total tropospheric ozone chemical production [196]. Ozone dry deposition dominantly occurs over vegetated surfaces via stomatal uptake on leaf surface and nonstomatal uptake on plant canopies [60, 243]. It is typically described separately by three processes: turbulent transport in aerodynamic layer, molecular diffusion through the quasi-laminar boundary layer, and uptake at the surface [213]. These mechanisms are commonly parameterized by analogy to the Ohms’ law that considers the deposition resistance (reciprocal of deposition velocity) as

electrical circuits: resistances in aerodynamic layer (R_A), quasi-laminar layer (R_B), and surface resistance (R_C).

Dry deposition is significantly influenced by meteorological conditions such as air stability and soil moisture. Strong air stability results in large R_A and impedes dry deposition. At daytime when turbulent is active (small R_A), ozone dry deposition is usually limited by R_C . R_C is further decomposed into stomatal uptake on leaf surface and nonstomatal uptake on plant canopies and ground, both linked to meteorological conditions. Stomatal ozone uptake is controlled by light that controls stomata activity and is also influenced by soil moisture and relative humidity. Drought and high temperature in air or soil would suppress stomatal uptake (therefore suppress dry deposition) due to the closure of stomata to protect plants from desiccation. This mechanism significantly influences ozone in semi-arid regions such the Mediterranean [4] and helps to explain the negative ozone-humidity correlations in the US [89]. Model results also showed that reductions of ozone dry deposition due to persistent high temperatures and drought could contributed to high ozone levels in Europe [179] and China [119]. The nonstomatal ozone deposition, which describes the thermal decomposition of ozone with external surfaces including soil and canopy, also shows some degrees of dependence on temperature and solar radiation [123]. A recent modeling study showed that the Monin-Obukhov length (a parameter for quantifying air stability) and surface temperature, were respectively, key factors influencing model estimates of ozone dry deposition velocity during nighttime and daytime [241].

To our knowledge, the responses of ozone dry deposition to future climate change have not yet been comprehensively quantified. There is one effort by Andersson and Engardt [5], which found that in winter decreasing snow cover in warmer future climate would lead to more effective ozone dry deposition, while in summer, changes in air stability, soil moisture, and temperature would lead to increase aerodynamic and surface resistances (therefore suppress ozone dry deposition). All these effects together led to ozone enhancements of up to 6 ppbv in Europe. They also found that the weaker dry deposition explained more than 60% of the total ozone enhancements, outweighed the effect from increasing biogenic isoprene emissions, implying the important role of dry deposition in climate-induced future ozone changes.

Effect on Ozone and Precursor Transport Patterns (Associated with Weather and Climate Patterns)

As the lifetime of tropospheric ozone and its precursors (e.g., CO, PAN) can reach weeks or months in the free troposphere [229], it allows shifts of transport patterns (typically associated with weather and climate patterns) to influence

tropospheric ozone by redistributing them. Based on the spatial scales, these weather patterns can be classified as synoptic circulations (~ 1000 km), large-scale climate patterns (~ 10,000 km), and global vertical circulations (e.g., [47, 82]). The physical mechanisms of ozone response to these weather patterns have been documented from ground-based measurements, satellite observations, and modeling studies. This section will focus on a “transport” perspective and also combine with discussions in the “Effect on Natural Sources of Ozone Precursors” and “Effect on Ozone Chemistry and Deposition” sections to illustrate that the responses are often associated with changes in natural emissions and chemistry. We will start with the response of tropospheric ozone to STE (associated with large-scale circulation, “STE and Large-Scale Meridional Circulations” section), to large-scale climate variability (~ 10,000 km) such as ENSO and AMO (“Large-Scale Climate Patterns (ENSO, AMO, NAO)” section), and then changes driven by synoptic circulations (~ 1000 km) such as monsoons, subtropical highs, and mid-latitude jet streams (“Synoptic Patterns” section).

STE and Large-Scale Meridional Circulations

From a global and long-term perspective, STE is driven by the large-scale stratospheric meridional circulation known as the Brewer-Dobson circulation (BDC). BDC is characterized by upwelling from troposphere to stratosphere in the tropics, transport to the extratropical stratosphere, and descending from stratosphere to troposphere at middle and high latitudes [185]. STE also occurs episodically at mid-latitudes associated with synoptic scale and mesoscale processes, such as tropopause folds near the jet streams, gravity wave breaking, and deep convections [185, 193]. The role of STE in modulating tropospheric ozone (550 Tg year^{-1} , approximately 10% of the annual global tropospheric ozone chemical production) and surface ozone has been well documented [67, 73, 178, 195].

BDC has been strengthening and is expected to further intensify in the warming future [16]. Increasing tropospheric greenhouse gases and depletion of polar stratospheric ozone (particularly in the Southern Hemisphere) can intensify meridional temperature gradient in the upper troposphere/lower stratosphere (UTLS) region, which enhances planetary wave activity and strengthens the BDC [16]. It then leads to ozone increase in the mid-latitude lower stratosphere and further descends to the troposphere [38, 187, 234]. Hegglin and Shepherd [65] showed that STE ozone transport would enhance by 23% in 2095 compared to the 1965 conditions due to strengthening BDC in the IPCC A1B scenario. Banerjee et al. [11] showed that future climate change alone would increase STE by 17% and 28% in 2100 compared to 2000 conditions for RCP 4.5 and RCP8.5 scenarios, respectively. A more recent study estimated a larger enhancement of STE by 50% for RCP 8.5 [122]. The implications for future ozone

change will be discussed in details in the “Future Ozone Change Due to Climate Change” section.

Tropospheric ozone is also affected by changes in strength and location of the subtropical jet streams or mid-latitude storm tracks where episodic STE occurs [72, 100]. There is observational evidence that subtropical jet streams and mid-latitude storm tracks have been moving poleward (a feature also diagnosed as widening of the Hadley Circulation/tropical belt) [74, 80, 121, 227] most likely caused by changes in meridional temperature gradients in the UTLS [115, 194]. A recent study by Lu et al. [120] attributed the large-scale positive tropospheric ozone trends in the Southern Hemisphere over 1990–2010 to widening of the Hadley circulation, by demonstrating the resulting changes in transport patterns favored stronger STE and ozone chemical production in the Southern Hemisphere. Positive tropospheric ozone trends at individual sites were also reported and linked to stronger STE (e.g., [112, 139]). Xu et al. [221] showed that increasing STE likely associated with strengthening of the mid-latitude jet stream explained approximately 70% of the observed spring-time ozone enhancements at Mt. Waliguan Observatory (3816 m) in western China over 1994–2013. Linkages between STE and climate variabilities such as ENSO and the North Atlantic Oscillation (NAO) have also been reported and will be discussed in the next section.

Large-Scale Climate Patterns (ENSO, AMO, NAO)

ENSO

ENSO is one of the dominant climate models that modulates global climate variability and also influences tropospheric ozone on the interannual timescale. In the El Niño condition, tropospheric ozone decreases (increases) in the eastern (western) Pacific regions, as illustrated by negative (positive) correlations between the Niño 3.4 Index and tropospheric column ozone (TCO) over the Pacific seen from satellite observations and model simulations [136–138, 248]. These responses can be explained by changes in zonal transport patterns. In the El Niño condition, the warm ocean shifts eastward into the coasts adjacent to the South America. Abnormal air upwelling above the warmer water in the eastern Pacific lifts the ozone-poor marine air and lowers TCO. Meanwhile, strengthened subsidence occurs in the western Pacific, increasing ozone concentrations there.

Besides influencing transport pathways, ENSO also affects ozone through altering chemistry and precursor emissions. Abnormal uplift in the eastern Pacific in El Niño brings more water vapor (sources of HO_x) into atmosphere, leading to stronger ozone chemical loss ((9) and (10)). The drier western Pacific is, in contrast, more favorable for ozone production than that in La Niña. Sekiya and Sudo [165] showed that although the impacts from transport outweighed those from

chemistry globally, they were comparable over the central Pacific. Warmer and drier weather conditions in the western Pacific during El Niño also promote biomass burning there [176] and enhance lightning activity as discussed in the “Lightning NO_x Emission” section, both contributing to higher ozone [237]. The response of tropical tropospheric ozone to ENSO therefore well illustrates that climate influences ozone through a conjunction of pathways of natural precursor sources, chemistry, and transport.

While the ozone-ENSO response is most significant in tropics, it can expand to mid-latitudes. The El Niño condition, also characterized as easterly shear Quasi-Biennial Oscillation (QBO) phase [100, 131, 247], can enhance STE at mid-latitudes due to stronger subtropical jet than La Niña [166]. Zeng and Pyle [233] found that STE increased the global tropospheric ozone burden by about 4 Tg following the strong 1997–1998 El Niño event. Regionally, higher TCO (4.9 DU) over the Europe in spring 1998 was found associated with stronger STE, Asian pollution transport, and wildfires [94]. Shifts in the polar stream position after La Niña winter have shown to increase frequency of deep stratospheric ozone intrusion events in the western US [111]. Changes in meteorological conditions and transport patterns in El Niño years have also found to cause surface ozone increases in the eastern US but decreases in the southern and western parts [169, 220]. On a 30-year time scale, Lin et al. [110] found that weaker transport from Eurasia to Mauna Loa (Hawaii) observatory, driven by more frequent occurrence of La-Niña-like conditions from 1980 to 2011, contributed to the flattening of springtime ozone, which offset the ozone enhancement due to increasing anthropogenic emissions.

AMO

On the multi-decadal timescales, AMO exerts considerable influences on the global and regional meteorological variability (e.g., [21]). To our knowledge, only a few studies have examined its influence on ozone air quality [170, 173, 223]. AMO is a climate cycle that features positive sea surface temperature (SST) anomalies in the northern Atlantic in its warm phase. Since 1900s, there have been warm AMO phases over 1931–1960 and 1990–2012 and cold phases in 1900–1929 and 1960–1994 [173, 189]. In the warm phase, warming Atlantic SSTs can trigger diabatic heating in the atmosphere, which further influences the extratropical climate through stationary wave propagations [189, 190]. This results in hotter, drier, and more stagnant weather in the eastern US and favors high ozone concentrations there. Understanding such linkages between ozone and SST [225] is particularly valuable because sea heat content has longer memory than atmosphere and can serve as a potential tool to predict ozone air quality. Shen et al. [173] estimated that in one half cycle of AMO (~35 years) from its cold to warm phase, the

summertime ozone levels in the US could increase by about 1–3 ppbv in the Northeast and 2–5 ppbv in the Great Plains. Yan et al. [223] also showed that AMO and ENSO indices could explain ~40% of the interannual variability of ozone concentrations in the US.

NAO and AO

Other climate oscillations such as the Arctic Oscillation (AO) and NAO have been found to influence tropospheric ozone at mid-high latitudes [28, 66]. In the positive AO phase, characterized by weaker sea level pressure in the polar region but higher sea level pressure at mid-latitudes, the weakened poleward transport from mid-latitudes to Arctic led to lower ozone (–1 DU) over the Arctic [165]. The variability of AO has shown to account for up to 50% of the observed ozone variability in the lower troposphere over North America in summer via changes in STE and intercontinental transport of ozone and its precursors [98]. The positive NAO phase intensifies the temperature gradient in the upper troposphere between mid-latitudes (~50° N) and high-latitudes (north of 60° N), and then affect the position of storm tracks and intensity. It is thus likely to strengthen STE [85] and influence surface ozone over Europe [143].

Synoptic Patterns

Monsoon

Monsoon is characterized by distinct seasonal transitions of prevailing wind and precipitation [33, 206]. The most energetic monsoon system is the Asian-Australian monsoon system spanning over the South and East Asia [33]. During winter, northerly wind prevails over South and East Asia, brings dry and cool weather conditions. The prevailing southwesterly with the onset of summer monsoon brings clean and moist ocean air to the continental southeast Asia, enhances cloud covers and precipitations. Convections are also active in the summer monsoon seasons.

Satellite and in situ observations have shown declines of tropospheric ozone in southeast Asia from May to August with the evolution of summer monsoon [155]. Significant ozone decreases over India could be attributed to transport pattern shifts, i.e., cleaner marine air input and stronger air uplift [156], and also lower ozone chemical production as a result of cloudy, cooler, and wetter weather conditions [135]. By quantifying the individual processes, Lu et al. [117] showed that the ozone chemical production decreased by 4.2 Tg over the Indian lower troposphere (from surface to 600 hPa) from May to August, and strong convection in August effectively uplifted 3.3 Tg ozone to above 600 hPa, together led to significant decreases in the Indian lower tropospheric ozone in the summer monsoon month. The uplifted

ozone in tropics can then be transported by the easterly jet in the upper troposphere and impact global tropospheric ozone distribution [96, 102, 106]. Similar ozone-monsoon responses but with different seasonal variations were also found for near-surface ozone in China [34, 62, 107, 118, 207, 240, 242].

Interannual ozone variability in monsoon regions shows strong correlations with the monsoon strength. Lu et al. [117] showed that ozone concentrations in the lower troposphere (from surface to 600 hPa) were 3.4 ppbv higher in weaker monsoon years than stronger years, mainly due to stronger ozone net chemical production. This negative correlation between ozone levels and monsoon strengths is also found at Pacific Ocean sites near the Asian continent [71]. Yang et al. [224], however, showed that stronger East Asian summer monsoons led to higher surface ozone concentrations over central and western China, mainly attributed to smaller ozone outflow to the East China Sea. Asian summer monsoon circulations are further modulated by climate variabilities such as ENSO [95] and AMO [114], and are projected to change in the warming future [157]. We thus expect these climate variabilities could also influence tropospheric ozone through change in monsoon on a longer timescale, which is still unknown due to the lack of long-term ozone observations.

Cyclone and Stagnation

The cold fronts associated with the mid-latitude cyclones can effectively lower air pollution [105, 197]. The frequency of ozone episodes in the northeastern US has showed a strong negative correlation with the cyclone frequency [105]. These cyclone activities are often related to the position of the polar jet wind. Combining observations and model simulations, Barnes and Fiore [12] found that the daily variability of US surface ozone was linked with the north-south latitudinal shift of the jet winds. Shen et al. [171] showed that the frequency of the jet wind traversing the Midwest and Northeast US acted as a good metric to diagnose the ozone variability in the northern US.

Surface ozone in Europe is strongly impacted by the strength and frequency of high-latitude blocks and subtropical ridges in summer [140]. A recent review from Dayan et al. [30] concluded that high summertime tropospheric ozone over the eastern Mediterranean could be attributed to frequent STE associated with tropopause folding activities [198], strong air subsidence at mid-troposphere [232], and the long-range transport of ozone-rich air masses from eastern continental Europe [154]. Myriokefalitakis et al. [128] suggested that the contribution of these dynamic processes (~90%) significantly outweighed that of local precursor emissions. High summertime ozone concentrations over the UK were often associated with anti-cyclonic conditions (degrading ventilation) and the easterly flows (transporting pollution from the continental Europe to the UK) [147].

Similar with front activities, stagnant conditions have been applied to diagnose air quality. Stagnations, which are usually characterized by slow wind speeds, no precipitation, and temperature inversion in the boundary layer, are unfavorable for ventilation and tend to build up high ozone air pollution [186]. High temperature events (heatwaves) could occur associated with stagnations under persistent high-pressure systems, leading to high ozone extremes [161, 172, 188]. Solberg et al. [179] summarized that during the 2003 Europe heatwave events, high ozone extremes were contributed by (1) extended air residence time in the stable boundary layer, (2) biomass burning due to drought and heat, (3) high biogenic isoprene emissions, and (4) reduced ozone dry deposition velocity. Sun et al. [188] showed that on average one stagnation day could increase the mean surface ozone concentration in the north-eastern US by about 4.7 ppbv.

Subtropical High

The semi-permanent subtropical high-pressure systems are mainly confined to oceans, but their intensifications in summer exert large influences on regional weather and air quality in regions such as the eastern US and eastern China [37, 43, 171, 239, 244]. Shen et al. [171] found that the influences of the Atlantic subtropical high (known as the Bermuda High) on ozone over the US depended on the location of its west boundary. The westward shift of the Bermuda High could increase ozone concentrations in regions under the high-pressure system, but decrease ozone along its west boundary by bringing clean and humid air from the ocean. Wang et al. [209] further showed that the location and strength of the Bermuda High explained 60–70% of the interannual variability of summertime ozone concentrations in the Houston–Galveston–Brazoria (HGB) metropolitan region. Focused on ozone air quality in China, Zhao and Wang [239] found that intensified West Pacific subtropical high enhanced southwesterly transport of moisture and clean air into South China, and therefore decreased ozone levels, but led to dry and sunny conditions over North China and thus increased ozone levels there.

Future Ozone Change Due to Climate Change

Previous sections have summarized three pathways of climatic influences on tropospheric ozone. In this section, we examine their combined effects in the context of future climate change. A review of future ozone projections driven by climate change was previously conducted by Jacob and Winner [82] and updated by Fiore et al. [46, 47] with more focus on the US. Here, we extend to more recent results (published after Jacob and Winner [82]), and include broader regional results.

Along with global warming driven by increasing greenhouse gas levels, there will be increases in the frequency,

duration, and intensity of regional hot extremes [25]. Hydrological cycle (water content, cloudiness, wet convections) will also respond to the warming. Global averaged specific humidity tends to increase due to more water vapor that can be accommodated in a warmer atmosphere, but relative humidity over land is expected to decline. There have also been some studies focusing on the future change of transport pattern (e.g., [36]). As discussed in the “[STE and Large-Scale Meridional Circulations](#)” section, increasing greenhouse gases will likely lead to accelerated stratospheric BDC and widening of the Hadley Circulation, which are expected to enhance STE in the future. Model projections show decreases of mid-latitude cyclone frequency due to poleward shift of polar jet stream over the eastern US in the twenty-first-century climate [103, 167, 227], and degradation of ventilation conditions with increasing stagnation days [70, 145].

Table 1 lists recent model projected future changes in surface or tropospheric ozone driven by climate change alone. The projections are from state-of-art chemical models with different frameworks (offline chemical transport model or on-line chemistry-climate model), model capability (dynamics, representation of natural emissions, and chemical mechanisms), model resolution, future greenhouse gas scenarios, time slice, and reported metrics. All these differences contribute to a wide range of projected ozone changes even for the same region [46, 47].

Despite different regional characteristics, most models predicted future climate change would lead to increases of surface ozone over polluted regions and decreases over remote land and oceans. Significant surface ozone enhancements were predicted in East Asia, Europe (in particular the southern Europe), and the northeastern US. Most models attributed surface ozone increases to warming-induced BVOC emission enhancements, faster chemistry kinetics, and also faster PAN decomposition. Only one result (Tai et al., 2013) listed in Table 1 included CO₂ inhibition on BVOC emissions. They showed that surface ozone enhancements would be reduced by 50% in major polluted regions when the CO₂ inhibition effect was included in the model. Over remote land and oceans, future surface ozone levels would generally decrease due to more water vapor and less PAN decomposition.

The different responses of surface ozone to future climate suggest “the most ozone polluted regions get worse while their neighbors get better” [162]. This is evident by more frequent occurrence of high ozone events (extremes) (e.g., [101, 104, 172, 208, 212]). For example, the 95th percentile of daily maximum 8-h average (MDA8) surface ozone in the US was projected to increase from 79 to 87 ppbv under the IPCC A2 scenario [146]. The increases of ozone extremes can be induced by a combined effect of higher ozone-temperature response in high NO_x regions [150], and more frequent and severe stagnations [70, 145] accompanied with persistent hot weather conditions [50, 172].

We highlight here the importance of increasing STE on future tropospheric ozone burden. Three projections ([11, 90]; and [122]) listed in Table 1 included stratosphere-resolved chemistry and dynamics in the models and thus better represent stratospheric influences on tropospheric ozone. All three models revealed significant enhancements of STE driven by stronger BDC, leading to increases of tropospheric ozone burden. Banerjee et al. [11] found that under the RCP8.5 scenario, climate change alone would indeed decrease net ozone chemical production (−109 Tg) due to higher water vapor content, but would then be compensated by increases of STE (+101 Tg), and result in a 13% increase of the tropospheric ozone burden. These results emphasized the need to better simulate STE in future ozone projections, however, many models (e.g., about half of the models in the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) Phase 1; [99]) and most results listed in Table 1 still used prescribed stratospheric ozone as the lateral boundary or linearized stratospheric ozone schemes for future projections. Future studies are needed to understand to what extent the increasing STE influences future surface ozone air quality.

Feedback from Tropospheric Ozone Change to Climate

While tropospheric ozone is affected by climate change, its variations in turn influence climate through altering radiation and atmosphere-biosphere interactions. Using 17 different global climate-chemistry models with varying radiation schemes, Stevenson et al. [184] estimated the tropospheric ozone radiative forcing of 410 mW m^{−2} from the pre-industrial era (1750) to 2010. Compared to CO₂ and methane, the shorter lifetime of tropospheric ozone leads to heterogeneous spatial distributions of its abundance and resulting radiative forcing. The highest tropospheric ozone radiative forcing values are found over the northern mid-latitudes where the sources of ozone precursors are large, and over cloudless subtropical regions such as the Sahara Desert where vertical temperature differences are high [184].

The heterogeneous distribution of ozone radiative forcing may alter atmospheric general circulation. High tropospheric ozone and black carbon levels at the northern mid-latitudes intensify the meridional temperature gradient in the UTLS, and partly drive the observed expansion of the Northern Hemisphere tropics [2]. As discussed in the “[STE and Large-Scale Meridional Circulations](#)” section, widening of the tropics (also the Hadley Circulation) may further increase tropospheric ozone, providing a potential positive feedback [120]. Exclusion of ozone radiative feedback in CCMs would also cause models to predict stronger weakening of the Walker circulation and more ENSO extremes in the future [133]. In

Table 1 Recent (since 2009) projections of future tropospheric ozone driven by climate change (abbreviation for model type: CM = climate model, RCM = regional CM, CTM = chemical transport model, RCTM = regional CTM, GCM = general circulation model, CCM = climate chemistry model; abbreviation for scenario: IPCC A1B/A2 scenarios [129], RCP 2.6/4.5/6.0/8.5; Representative Concentration Pathways (RCP) scenarios with radiative forcing of 2.6/4.5/6.0/8.5 W m⁻² by 2100 [202]; abbreviation for metrics: MDA8 = daily maximum 8-h average, JJA = June–July–August, DJF = December–January–February; abbreviation for regions: NE = northeast, SE = southeast, IMW = Intermountain West, NA = North America, EU = Europe, EA = East Asia, SA = South Asia; note that domains can be different among studies)

Reference	Type (resolution)	Region	Scenario	Time horizon	Metric	Ozone change (uncertainty if provided)	Important contribution factors (with +/- signs denoting directions of global ozone change)
Kawase et al. [90] #	CCM (2.8°×2.8°)	Globe	RCP 8.5	2100 vs. 2005	Annual mean tropospheric ozone column (DU)	+ 5.5	1) Increase in STE (+) 2) Higher water vapor concentrations (-)
Doherty et al. [35]	3 CCMs (5°×5° to 3.75°×2.5°)	Globe	IPCC A2	2095–2099 vs. 2001–2005	Annual surface average ozone (ppbv or %)	NA: -2.2% (-1.4 to -3.4%) ^a EU: -1.0% (-2.0 to +0.4%) EA: -1.6% (-2.9 to +0.2%) Polluted region: +6 ppbv	Globe: 1) Decrease in PAN decomposition (-) 2) Higher water vapor concentrations (-) Polluted regions: 1) Increase in PAN decomposition (+) 2) Increasing BVOC emissions (+) 3) Higher water vapor concentrations (-)
Tai et al. [191]*	GCM-CTM (5°×4°)	Globe	IPCC A1B	2050 vs. 2000	Surface summertime MDA8 ozone (ppbv)	NA, EU, EA: maximum of +6 (NOT include CO ₂ inhibition) NA, EU, EA: maximum of +3 (include CO ₂ inhibition)	1) Increase in PAN decomposition (+) 2) Increasing BVOC emissions (+)
Banerjee et al. [11] #	CCM (3.75°×2.5°)	Globe	RCP 8.5	2100 vs. 2000	Annual mean tropospheric ozone burden (Tg or %)	+43Tg or 13.1%	1) Increase in STE (+) 2) Higher water vapor concentrations (-)
Schnell et al. [162]	4 CCMs (2°×2° to 3.75°×2.5°)	Globe	RCP 8.5	2100 vs. 2000	Surface summertime MDA8 ozone (ppbv)	West NA: -0.2 (-2.1 to +5.0) ^a East NA: +1.8 (-2.2 to +7.3) South EU: +2.0 (-1.3 to +9.3) North EU: -0.9 (-3.9 to +2.0) South EA: -2.8 (-4.7 to -0.8) North EA: -0.5 (-2.5 to +3.1) +112 Tg or 28%	1) Increasing BVOCs emissions (+) 2) Faster kinetics (+) 3) More stagnations (+) 4) Higher water vapor concentrations (-)
Meul et al. [122] #	CCM (2.8°×2.8°)	Globe	RCP8.5	2100 vs. 2000	Tropospheric ozone burden (Tg or %)		1) Increase in STE (+)

Table 1 (continued)

Reference	Type (resolution)	Region	Scenario	Time horizon	Metric	Ozone change (uncertainty if provided)	Important contribution factors (with +/- signs denoting directions of global ozone change)
Hedegaard et al. [64]	GCM-RCTM (N/A)	NH	RCP 4.5	2090–2099 vs. 1990–1999	Annual surface ozone (%)	Arctic: +5 to +10 ^b EU, US, and SE Asia: +5 to +20 Remote: -10 to -5	1) Higher ozone import to Arctic (+) 2) Less ozone dry deposition in the Arctic (+) 3) Increasing BVOC emissions (+) 4) Higher water vapor concentration (-)
Andersson and Engardt [5]	RCM-CTM (0.44°×0.44°)	Europe	IPCC A2	2071–2100 vs. 1961–1990	April–September surface daily maximum ozone (ppbv)	-3 to +25 ^b	1) Decreasing dry deposition (+) 2) Increasing BVOC's emission (+)
Karagkou et al. [88]	RCM-RCTM (50×50 km)	Europe	A1B	2091–2100 vs. 1991–2000	Median JJA surface ozone (ppbv)	+3.9 to +6.2 ^b	1) Decreasing cloudiness (+) 2) More stagnant condition (+) 3) Increasing BVOC emission (+)
Langner et al. [101]	5 GCM-RCM-RCTM/RC-CM (150×150 to 50×50 km)	Europe	A1B	2040–2049 vs. 2000–2009	Maximum positive changes in April–September surface mean ozone (ppbv)	+2.7 (+1.2 to +3.0) ^a	1) Increasing BVOC emission (+)
Colette et al. [23]	GCM-CTM (3.75°×2.5°)	Europe	RCP8.5	2045–2054 vs. 1996–2005	JJA surface MDA8 ozone (μg m ⁻³)	Below +1	1) Increasing BVOC emissions (+)
Colette et al. [24]	11 all-type models (5°×5° to 0.44°×0.44°)	Europe	Multi-scenario	2070–2100 vs. 2000s	JJA surface ozone (ppbv)	EU: +1.25 (+0.99 to +1.5) ^e Alps: +5	1) Increasing BVOC emissions (+)
Watson et al. [211]	4 GCM-RCTMs (50×50 km)	Europe	RCP 4.5	2050 vs. 2006	Surface mean ozone (ppbv)	JJA: +0.36 (-0.11 to +0.83) ^a DJF: +0.05 (-0.21 to +0.26)	No dominant drivers are concluded
Avisé et al. [8]	RCM-CTM (36×36 km)	US	IPCC A2	2045–2054 vs. 1990–1999	July surface MDA8 ozone (ppbv)	NE US: +1 to +4 ^b SE US: -6 to -1	1) NE US: increasing temperature (+) 2) SE US: increasing precipitation decrease organic nitrates (-)
Weaver et al. [212]	12 all-type models (4–36 km; 0.44°×0.44° to 5°×4°)	US	Multi-scenario	End of twenty-first century vs. present	JJA surface MDA8 ozone (ppbv)	NE US: 0 to +4 ^a IMW: -2 to +3 SE US: -6 to +5	1) Increasing BVOC's emissions (+) 2) Increasing solar radiation and temperature (+)
Lam et al. [97]	GCM/RCM-RCTM (12×12 km)	US	A1B	2050 vs. 2000	Annual surface MDA8 ozone (ppbv)	+2.0 to +2.5 on average	1) Increasing BVOC's emissions (+)

Table 1 (continued)

Reference	Type (resolution)	Region	Scenario	Time horizon	Metric	Ozone change (uncertainty if provided)	Important contribution factors (with +/- signs denoting directions of global ozone change)
Kelly et al. [91]	RCM-RCTM (45 × 45 km)	US	A2	2041–2050 vs. 1997–2006	JJA surface MDA8 ozone (ppbv)	+ 9 to + 10 in urban region	1) Increasing temperature and solar radiation (+)
Clifton et al. [22]	CCM (2° × 2°)	US	RCP8.5	2091–2100 vs. 2006–2015	JJA surface ozone (ppbv)	NE US: + 3 IMW US: - 4 to - 1 ^b Maximum of + 10	1) NE US: decrease in cyclone frequency (+) 2) IMW US: higher water vapor concentrations (-)
Pfister et al. [146]	GCM-RCCM (36 × 36 km)	US	A2	2046–2058 vs. 1996–2008	JJA surface MDA8 ozone (ppbv)	Maximum of + 10	1) Increasing solar radiation and decreasing cloudiness (+) 2) Increasing BVOC emission (+)
Rieder et al. [151]	CCM (48 × 48 km)	Eastern US	RCP 4.5	2091–2100 vs. 2005	JJA surface MDA8 ozone (ppbv)	+ 1 to + 2 on average, maximum of + 4	1) Decrease in cyclone frequency (+)
Gonzalez-Abraham et al. [54]	GCM-RCTM (36 × 36 km)	US	A1B	2045–2054 vs. 1995–2004	JJA surface MDA8 ozone (ppbv)	NW US: - 1.0 Other regions in US: + 0.4 to 7.2	NWUS: decreasing in solar radiation (-) Others: 1) Increasing solar radiation (+) 2) Increasing temperature (+)
Val martin et al. [201]	CCM (2.5° × 1.9°)	US	RCP 8.5	2050 vs. 2000	Annual surface MDA8 ozone (ppbv)	US: + 2 Eastern US: maximum of + 5	1) Increasing BVOCs emissions (+) 2) Decreasing dry deposition velocity (+) 3) Decreasing precipitation (+)
Nolte et al. [132]	GCM-RCM-CTM (1.25° × 0.9°)	US	RCP 8.5	2030 vs. 2000	JJA surface MDA8 ozone (ppbv)	+ 0.2 to + 2.9 ^b	1) Increasing BVOC emissions (+)
Wang et al. [208]	GCM-CTM (5° × 4°)	China	A1B	2050 vs. 2000	Annual surface mean ozone (ppbv)	Eastern China: + 0.5 to + 3 ^b Western China: - 2 to - 0.1	1) Eastern China: increasing BVOCs emission (+) 2) Western China: higher water vapor concentrations (-)

*The model considered CO₂ inhibition for biogenic isoprene emission as discussed in the “BVOC Emissions” section

#The study considered full stratosphere dynamics and chemistry and discussed the impact on tropospheric ozone change

^aNumbers are ranges among individual models^bNumbers are ranges among different regions or model grids^cNumbers are 95% confidence interval

addition, tropospheric ozone can influence the radiative forcing of other chemical tracers such as methane and NO_x by changing their lifetimes [44, 47].

Tropospheric ozone also affects climate indirectly through its impacts on vegetation and carbon uptake [113, 177]. Stomatal uptake of ozone damages plant cells and impedes plant photosynthesis, leading to reductions of plant primary productivity [1, 39, 231]. Sitch et al. [177] estimated that under the IPCC A2 scenario, increasing tropospheric ozone in 2100 would decrease the global gross primary productivity by up to $30 \text{ Pg C year}^{-1}$ compared to the 1990 condition, exerting indirect radiative forcing of 1.09 W m^{-2} . The declined vegetation would decrease the amount of BVOC emissions, and therefore limit ozone production, but it would also suppress ozone dry deposition. Such interactions between climate, atmospheric chemistry, and the biosphere are still poorly understood and are generally not considered in current studies.

Conclusion

Variations and future changes of tropospheric ozone are strongly tied to meteorology and climate (Fig. 1). Meteorology influences the biogenic activities of vegetation and microbes in the ecosystem and hence their emissions of ozone precursors. These climate-sensitive natural emissions mainly include soil NO_x , lightning NO_x , BVOCs, wildfires, and wetland methane emissions. Meteorology also determines the nature of atmosphere where photochemistry relies on, and therefore influences tropospheric ozone through altering the kinetics, and partitioning and deposition of chemicals. Changes in atmospheric circulation on different spatiotemporal scales influence the transport of ozone and its precursors. In particular, robust signals of ozone response have been found to large-scale circulations (e.g., BDC) and STE, large-scale climate patterns (e.g., ENSO, AMO), and synoptic patterns (e.g., monsoon, cyclones). All these connections together determine the high sensitivity of tropospheric ozone levels to climate.

Projections of future ozone changes driven by climate change largely reflect the dominant role of increasing temperature and water vapor in the atmosphere. These suggest increasing surface ozone in the polluted regions such as eastern US, southern Europe, and the south and east Asia, most likely due to increasing biogenic isoprene emissions, increasing solar radiation with less cloudiness, decreasing ozone dry deposition, increasing PAN decomposition, and higher frequency of stagnations and heat waves. Additional emission control measures are thus required over such regions to meet the ozone air quality standards in the future. In remote regions and ocean, surface ozone levels are projected to decrease due to stronger chemical loss with higher water vapor and also less PAN decomposition. The change of tropospheric ozone

burden can be affected by the competing roles of increasing water vapor (which decreases tropospheric ozone) and increasing STE due to stronger BDC (which increases tropospheric ozone).

Considerable limits still exist in the current understanding of the biogenic, chemical, and dynamic linkages between ozone and climate, which challenge our confidence in the model projections of future ozone change. Previous reviews have raised some major recommendations, e.g., improving the capability of climate models to present local processes, constraining uncertainties in atmospheric chemistry mechanisms (in particular the uncertain yield and fate of isoprene nitrates), and using ensemble model runs for future projections [46, 47, 82]. Here, we prioritize two important issues for further research and model development.

1. Uncertainties in biogenic activities and their responses to changing environment. The ecosystem serves as a hub to connect tropospheric ozone and climate, yet their linkages need to be better understood. Models may not adequately present many of these biogenic activities, for example, the inhabitation of BVOC emissions with rising CO_2 levels [191], biogenic isoprene emissions in rapid transition of weather conditions (e.g., [235]), and ozone damage on vegetation (further influence emission of BVOCs and uptake of ozone and carbon). Many models also do not consider the climate-induced terrestrial change (e.g., evolution of plant types and land cover), which has important implications for the ozone variation as many of the terrestrial responses are dependent on plant types [26]. Improved scientific knowledge as well as the development of fully coupled earth system models is in need to better quantify such interactions.

2. The role of future stratospheric circulation and STE on tropospheric ozone. As discussed in the “[Future Ozone Change Due to Climate Change](#)” section, models that predict stronger stratospheric BDC in the future show notable increases in tropospheric ozone burden driven by changes of STE, while models with no or inadequately stratosphere dynamics predicted tropospheric ozone decreases. Coupling with future stratosphere ozone recovery [32, 180], stronger STE may become a key factor modulating future tropospheric ozone and even surface ozone. Representing these dynamic ozone responses requires models to include stratosphere-resolved dynamics and chemistry.

Finally, we also briefly review the feedback of tropospheric ozone to climate change through exerting RF and interactions with biosphere. The heterogeneous spatial distribution of tropospheric ozone exerts notable influences on the global and regional scale atmospheric circulations such as the Hadley Circulation and the Walker Circulation. The increasing surface ozone also impedes the carbon uptake in ecosystem and therefore indirectly influence climate. A comprehensive view of the interactions between tropospheric ozone, ecosystem, and radiation remains to be quantified in future studies.

Funding Information This work is supported by the National Key Research and Development Program of China (2017YFC0210102) and the National Natural Science Foundation of China (41475112).

Compliance with Ethical Standards

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

- Ainsworth EA, Yendrek CR, Sitch S, Collins WJ, Emberson LD. The effects of tropospheric ozone on net primary productivity and implications for climate change. *Annu. Rev. Plant Biol.* 2012;63: 637–61. <https://doi.org/10.1146/annurev-arplant-042110-103829>.
- Allen RJ, Sherwood SC, Norris JR, Zender CS. Recent Northern Hemisphere tropical expansion primarily driven by black carbon and tropospheric ozone. *Nature.* 2012;485(7398):350–4. <https://doi.org/10.1038/nature11097>.
- Alvarado MJ, Logan JA, Mao J, Apel E, Riemer D, Blake D, et al. Nitrogen oxides and PAN in plumes from boreal fires during ARCTAS-B and their impact on ozone: an integrated analysis of aircraft and satellite observations. *Atmos. Chem. Phys.* 2010;10(20):9739–60. <https://doi.org/10.5194/acp-10-9739-2010>.
- Anav A, Proietti C, Menut L, Carnicelli S, De Marco A, Paoletti E. Sensitivity of stomatal conductance to soil moisture: implications for tropospheric ozone. *Atmos Chem Phys.* 2018;18(8):5747–63. <https://doi.org/10.5194/acp-18-5747-2018>.
- Andersson C, Engardt M. European ozone in a future climate: Importance of changes in dry deposition and isoprene emissions. *J Geophys Res.* 2010;115(D2). <https://doi.org/10.1029/2008jd011690>.
- Arneth A, Niinemets Ü, Pressley S, Bäck J, Hari P, Karl T, et al. Process-based estimates of terrestrial ecosystem isoprene emissions: incorporating the effects of a direct CO₂–isoprene interaction. *Atmos Chem Phys.* 2007;7(1):31–53. <https://doi.org/10.5194/acp-7-31-2007>.
- Atkinson R. Atmospheric chemistry of VOCs and NO_x. *Atmos. Environ.* 2000;34(12–14):2063–101. [https://doi.org/10.1016/S1352-2310\(99\)00460-4](https://doi.org/10.1016/S1352-2310(99)00460-4).
- Avise J, Chen J, Lamb B, Wiedinmyer C, Guenther A, Salathé E, et al. Attribution of projected changes in summertime US ozone and PM_{2.5} concentrations to global changes. *Atmos Chem Phys.* 2009;9(4):1111–24. <https://doi.org/10.5194/acp-9-1111-2009>.
- Baertsch-Ritter N, Keller J, Dommen J, Prevot ASH. Effects of various meteorological conditions and spatial emission resolutions on the ozone concentration and ROG/NO_x limitation in the Milan area (I). *Atmos Chem Phys.* 2004;4(2): 423–38. <https://doi.org/10.5194/acp-4-423-2004>.
- Banerjee A, Archibald AT, Maycock AC, Telford P, Abraham NL, Yang X, et al. Lightning NO_x, a key chemistry–climate interaction: impacts of future climate change and consequences for tropospheric oxidising capacity. *Atmos Chem Phys.* 2014;14(18):9871–81. <https://doi.org/10.5194/acp-14-9871-2014>.
- Banerjee A, Maycock AC, Archibald AT, Abraham NL, Telford P, Braesicke P, et al. Drivers of changes in stratospheric and tropospheric ozone between year 2000 and 2100. *Atmos Chem Phys.* 2016;16(5):2727–46. <https://doi.org/10.5194/acp-16-2727-2016>.
- Barnes EA, Fiore AM. Surface ozone variability and the jet position: implications for projecting future air quality. *Geophys Res Lett.* 2013;40(11):2839–44. <https://doi.org/10.1002/grl.50411>.
- Bertram TH, Heckel A, Richter A, Burrows JP, Cohen RC. Satellite measurements of daily variations in soil NO_x emissions. *Geophys Res Lett.* 2005;32(24). <https://doi.org/10.1029/2005gl024640>.
- Bloom AA, Bowman KW, Lee M, Turner AJ, Schroeder R, Worden JR, et al. A global wetland methane emissions and uncertainty dataset for atmospheric chemical transport models (WetCHARTs version 1.0). *Geosci Model Dev.* 2017;10(6): 2141–56. <https://doi.org/10.5194/gmd-10-2141-2017>.
- Brasseur GP, Jacob DJ. Modeling of atmospheric chemistry. Cambridge University Press. 2017. <https://doi.org/10.1017/9781316544754>.
- Butchart N. The Brewer-Dobson circulation. *Rev Geophys.* 2014;52(2):157–84. <https://doi.org/10.1002/2013rg000448>.
- Camalier L, Cox W, Dolwick P. The effects of meteorology on ozone in urban areas and their use in assessing ozone trends. *Atmos Environ.* 2007;41(33):7127–37. <https://doi.org/10.1016/j.atmosenv.2007.04.061>.
- Cao MK, Gregson K, Marshall S. Global methane emission from wetlands and its sensitivity to climate change. *Atmos Environ.* 1998;32(19):3293–9.
- Carvalho A, Monteiro A, Flannigan M, Solman S, Miranda AI, Borrego C. Forest fires in a changing climate and their impacts on air quality. *Atmos Environ.* 2011;45(31):5545–53. <https://doi.org/10.1016/j.atmosenv.2011.05.010>.
- Christensen TR, Ekberg A, Ström L, Mastepanov M, Panikov N, Öquist M, et al. Factors controlling large scale variations in methane emissions from wetlands. *Geophys Res Lett.* 2003;30(7). <https://doi.org/10.1029/2002gl016848>.
- Chylek P, Klett JD, Lesins G, Dubey MK, Hengartner N. The Atlantic Multidecadal Oscillation as a dominant factor of oceanic influence on climate. *Geophys Res Lett.* 2014;41(5):1689–97. <https://doi.org/10.1002/2014gl059274>.
- Clifton OE, Fiore AM, Correa G, Horowitz LW, Naik V. Twenty-first century reversal of the surface ozone seasonal cycle over the northeastern United States. *Geophys Res Lett.* 2014;41(20):7343–50. <https://doi.org/10.1002/2014gl061378>.
- Colette A, Bessagnet B, Vautard R, Szopa S, Rao S, Schuch S, et al. European atmosphere in 2050, a regional air quality and climate perspective under CMIP5 scenarios. *Atmos Chem Phys.* 2013;13(15):7451–71. <https://doi.org/10.5194/acp-13-7451-2013>.
- 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):084015. <https://doi.org/10.1088/1748-9326/10/8/084015>.
- Collins M, Knutti R, Arblaster J, Dufresne J-L, Fichetef T, Friedlingstein P, et al. Long-term climate change: projections, commitments and irreversibility. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM, editors. Climate change 2013: the physical science

- basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2013.
26. Cooper OR. Detecting the fingerprints of observed climate change on surface ozone variability. *Science Bulletin*. 2019;64(6):359–60. <https://doi.org/10.1016/j.scib.2019.02.013>.
 27. Cooper OR, Stohl A, Trainer M, Thompson AM, Witte JC, Oltmans SJ, et al. Large upper tropospheric ozone enhancements above midlatitude North America during summer: In situ evidence from the IONS and MOZAIC ozone measurement network. *J Geophys Res*. 2006;111(D24). <https://doi.org/10.1029/2006jd007306>.
 28. Creilson JK, Fishman J, Wozniak AE. Arctic Oscillation-induced variability in satellite-derived tropospheric ozone. *Geophys Res Lett*. 2005;32(14). <https://doi.org/10.1029/2005gl023016>.
 29. Dawson JP, Adams PJ, Pandis SN. Sensitivity of ozone to summertime climate in the eastern USA: a modeling case study. *Atmos Environ*. 2007;41(7):1494–511. <https://doi.org/10.1016/j.atmosenv.2006.10.033>.
 30. Dayan U, Ricaud P, Zbinden R, Dulac F. Atmospheric pollution over the eastern Mediterranean during summer – a review. *Atmos Chem Phys*. 2017;17(21):13233–63. <https://doi.org/10.5194/acp-17-13233-2017>.
 31. Denman KL, Brasseur G. Couplings between changes in the climate system and biogeochemistry. *Clim Chang*. 2007; The Physical Science Basis, 2007:499–587.
 32. Dhomse SS, Kinnison D, Chipperfield MP, Salawitch RJ, Cionni I, Hegglin MI, et al. Estimates of ozone return dates from Chemistry-Climate Model Initiative simulations. *Atmos. Chem. Phys.* 2018;18(11):8409–38. <https://doi.org/10.5194/acp-18-8409-2018>.
 33. Ding Y, Chan JCL. The East Asian summer monsoon: an overview. *Meteorog Atmos Phys*. 2005;89(1–4):117–42. <https://doi.org/10.1007/s00703-005-0125-z>.
 34. Ding AJ, Fu CB, Yang XQ, Sun JN, Zheng LF, Xie YN, et al. Ozone and fine particle in the western Yangtze River Delta: an overview of 1 yr data at the SORPES station. *Atmos Chem Phys*. 2013;13(11):5813–30. <https://doi.org/10.5194/acp-13-5813-2013>.
 35. Doherty RM, Wild O, Shindell DT, Zeng G, MacKenzie IA, Collins WJ, et al. Impacts of climate change on surface ozone and intercontinental ozone pollution: a multi-model study. *J Geophys Res*. 2013;118(9):3744–63. <https://doi.org/10.1002/jgrd.50266>.
 36. Doherty RM, Orbe C, Zeng G, Plummer DA, Prather MJ, Wild O, et al. Multi-model impacts of climate change on pollution transport from global emission source regions. *Atmos Chem Phys*. 2017;17(23):14219–37. <https://doi.org/10.5194/acp-17-14219-2017>.
 37. Eder BK, Davis JM, Bloomfield P. A characterization of the spatiotemporal variability of non-urban ozone concentrations over the eastern United States. *Atmos Environ Part A*. 1993;27(16):2645–68. [https://doi.org/10.1016/0960-1686\(93\)90035-w](https://doi.org/10.1016/0960-1686(93)90035-w).
 38. Eyring V, Arblaster JM, Cionni I, Sedláček J, Perlwitz J, Young PJ, et al. Long-term ozone changes and associated climate impacts in CMIP5 simulations. *J Geophys Res*. 2013;118(10):5029–60. <https://doi.org/10.1002/jgrd.50316>.
 39. Felzer B, Reilly J, Melillo J, Kicklighter D, Sarofim M, Wang C, et al. Future effects of ozone on carbon sequestration and climate change policy using a global biogeochemical model. *Clim Chang*. 2005;73(3):345–73. <https://doi.org/10.1007/s10584-005-6776-4>.
 40. Finney DL, Doherty RM, Wild O, Huntrieser H, Pumphrey HC, Blyth AM. Using cloud ice flux to parametrise large-scale lightning. *Atmos Chem Phys*. 2014;14(23):12665–82. <https://doi.org/10.5194/acp-14-12665-2014>.
 41. Finney DL, Doherty RM, Wild O, Young PJ, Butler A. Response of lightning NO_x emissions and ozone production to climate change: insights from the Atmospheric Chemistry and Climate Model Intercomparison Project. *Geophys Res Lett*. 2016;43(10):5492–500. <https://doi.org/10.1002/2016gl068825>.
 42. 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):210–3. <https://doi.org/10.1038/s41558-018-0072-6>.
 43. Fiore AM, Jacob DJ, Mathur R, Martin RV. Application of empirical orthogonal functions to evaluate ozone simulations with regional and global models. *J Geophys Res-Atmos*. 2003;108(D19). <https://doi.org/10.1029/2002jd003151>.
 44. Fiore AM, West JJ, Horowitz LW, Naik V, Schwarzkopf MD. Characterizing the tropospheric ozone response to methane emission controls and the benefits to climate and air quality. *J Geophys Res*. 2008;113(D8). <https://doi.org/10.1029/2007jd009162>.
 45. Fiore AM, Levy II H, Jaffe DA. North American isoprene influence on intercontinental ozone pollution. *Atmos Chem Phys*. 2011;11(4):1697–710. <https://doi.org/10.5194/acp-11-1697-2011>.
 46. 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>.
 47. 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>.
 48. Fischer EV, Jacob DJ, Yantosca RM, Sulprizio MP, Millet DB, Mao J, et al. Atmospheric peroxyacetyl nitrate (PAN): a global budget and source attribution. *Atmos Chem Phys*. 2014;14(5):2679–98. <https://doi.org/10.5194/acp-14-2679-2014>.
 49. Fu T-M, Zheng Y, Paulot F, Mao J, 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>.
 50. Gao Y, Fu JS, Drake JB, Lamarque JF, Liu Y. The impact of emission and climate change on ozone in the United States under representative concentration pathways (RCPs). *Atmos Chem Phys*. 2013;13(18):9607–21. <https://doi.org/10.5194/acp-13-9607-2013>.
 51. Gaudel A, Cooper OR, Ancellet G, Barret B, Boynard A, Burrows JP, et al. Tropospheric Ozone Assessment Report: Present-day distribution and trends of tropospheric ozone relevant to climate and global atmospheric chemistry model evaluation. *Elementa-Sci Anthropol*. 2018;6. <https://doi.org/10.1525/elementa.291>.
 52. Gedney N. Climate feedback from wetland methane emissions. *Geophys Res Lett*. 2004;31(20). <https://doi.org/10.1029/2004gl020919>.
 53. Ghude SD, Lal DM, Beig G, van der A R, Sable D. Rain-induced soil NO_x emission from India during the onset of the summer monsoon: a satellite perspective. *J Geophys Res*. 2010;115(D16). <https://doi.org/10.1029/2009jd013367>.
 54. Gonzalez-Abraham R, Chung SH, Avise J, Lamb B, Salathé EP, 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>.
 55. Grewe V. Impact of climate variability on tropospheric ozone. *Sci Total Environ*. 2007;374(1):167–81. <https://doi.org/10.1016/j.scitotenv.2007.01.032>.
 56. Guenther AB, Monson RK, Fall R. Isoprene and monoterpene emission rate variability: observations with eucalyptus and emission rate algorithm development. *J Geophys Res*. 1991;96(D6):10799. <https://doi.org/10.1029/91jd00960>.
 57. Guenther A, Karl T, Harley P, Wiedinmyer C, Palmer PI, Geron C. Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature). *Atmos Chem Phys*. 2006;6(11):3181–210. <https://doi.org/10.5194/acp-6-3181-2006>.

58. Hamid EY, Kawasaki Z-I, Mardiana R. Impact of the 1997-98 El Niño Event on lightning activity over Indonesia. *Geophys Res Lett*. 2001;28(1):147–50. <https://doi.org/10.1029/2000gl011374>.
59. Hantson S, Knorr W, Schurgers G, Pugh TAM, 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>.
60. Hardacre C, Wild O, Emberson L. An evaluation of ozone dry deposition in global scale chemistry climate models. *Atmos Chem Phys*. 2015;15(11):6419–36. <https://doi.org/10.5194/acp-15-6419-2015>.
61. Hauglustaine DA, Lathière J, Szopa S, Folberth GA. Future tropospheric ozone simulated with a climate-chemistry-biosphere model. *Geophys Res Lett*. 2005;32(24). <https://doi.org/10.1029/2005gl024031>.
62. He YJ, Uno I, Wang ZF, Pochanart P, Li J, Akimoto H. Significant impact of the East Asia monsoon on ozone seasonal behavior in the boundary layer of Eastern China and the west Pacific region. *Atmos Chem Phys*. 2008;8(24):7543–55. <https://doi.org/10.5194/acp-8-7543-2008>.
63. Heald CL, Wilkinson MJ, Monson RK, Alo CA, Wang G, Guenther A. Response of isoprene emission to ambient CO₂ changes and implications for global budgets. *Glob Chang Biol*. 2009;15(5):1127–40. <https://doi.org/10.1111/j.1365-2486.2008.01802.x>.
64. Hedegaard GB, Christensen JH, Brandt J. The relative importance of impacts from climate change vs. emissions change on air pollution levels in the 21st century. *Atmos. Chem Phys*. 2013;13(7):3569–85. <https://doi.org/10.5194/acp-13-3569-2013>.
65. Hegglin MI, Shepherd TG. Large climate-induced changes in ultraviolet index and stratosphere-to-troposphere ozone flux. *Nat Geosci*. 2009;2(10):687–91. <https://doi.org/10.1038/ngeo604>.
66. Hess PG, Lamarque J-F. Ozone source attribution and its modulation by the Arctic oscillation during the spring months. *J Geophys Res*. 2007;112(D11). <https://doi.org/10.1029/2006jd007557>.
67. Hess PG, Zbinden R. Stratospheric impact on tropospheric ozone variability and trends: 1990–2009. *Atmos Chem Phys*. 2013;13(2):649–74. <https://doi.org/10.5194/acp-13-649-2013>.
68. Hodson EL, Poulter B, Zimmermann NE, Prigent C, Kaplan JO. The El Niño-Southern Oscillation and wetland methane interannual variability. *Geophys Res Lett*. 2011;38(8). <https://doi.org/10.1029/2011gl046861>.
69. Horne JR, Dabdub D. Impact of global climate change on ozone, particulate matter, and secondary organic aerosol concentrations in California: a model perturbation analysis. *Atmos. Environ*. 2017;153:1–17. <https://doi.org/10.1016/j.atmosenv.2016.12.049>.
70. Horton DE, Skinner CB, Singh D, Diffenbaugh NS. Occurrence and persistence of future atmospheric stagnation events. *Nat Clim Chang*. 2014;4:698–703. <https://doi.org/10.1038/nclimate2272>.
71. Hou X, Zhu B, Fei D, Wang D. The impacts of summer monsoons on the ozone budget of the atmospheric boundary layer of the Asia-Pacific region. *Sci. Total Environ*. 2015;502:641–9. <https://doi.org/10.1016/j.scitotenv.2014.09.075>.
72. Hsu J, Prather MJ. Stratospheric variability and tropospheric ozone. *J Geophys Res*. 2009;114(D6). <https://doi.org/10.1029/2008jd010942>.
73. Hu L, Jacob DJ, Liu X, et al. Global budget of tropospheric ozone: evaluating recent model advances with satellite (OMI), aircraft (IAGOS), and ozonesonde observations. *Atmos Environ*. 2017;167:323–34.
74. Hu Y, Huang H, Zhou C. Widening and weakening of the Hadley circulation under global warming. *Sci Bull*. 2018;63(10):640–4. <https://doi.org/10.1016/j.scib.2018.04.020>.
75. Hudman RC, Jacob DJ, Turquety S, Lebensperger EM, Murray LT, Wu S, et al. Surface and lightning sources of nitrogen oxides over the United States: Magnitudes, chemical evolution, and outflow. *J Geophys Res*. 2007;112(D12). <https://doi.org/10.1029/2006jd007912>.
76. Hudman RC, Russell AR, Valin LC, Cohen RC. Interannual variability in soil nitric oxide emissions over the United States as viewed from space. *Atmos Chem Phys*. 2010;10(20):9943–52. <https://doi.org/10.5194/acp-10-9943-2010>.
77. 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>.
78. Isaksen ISA, Granier C, Myhre G, Berntsen TK, Dalsøren 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>.
79. 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*. 2009;114(D9). <https://doi.org/10.1029/2008jd011254>.
80. Ivy DJ, Hilgenbrink C, Kinnison D, Alan Plumb R, Sheshadri A, Solomon S, et al. Observed changes in the southern hemispheric circulation in may. *J Clim*. 2017;30(2):527–36. <https://doi.org/10.1175/jcli-d-16-0394.1>.
81. Jacob D. Heterogeneous chemistry and tropospheric ozone. *Atmos Environ*. 2000;34(12-14):2131–59. [https://doi.org/10.1016/s1352-2310\(99\)00462-8](https://doi.org/10.1016/s1352-2310(99)00462-8).
82. 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>.
83. Jacobson MZ, Streets DG. Influence of future anthropogenic emissions on climate, natural emissions, and air quality. *J Geophys Res*. 2009;114(D8). <https://doi.org/10.1029/2008jd011476>.
84. Jaffe DA, Wigder NL. Ozone production from wildfires: a critical review. *Atmos Environ*. 2012;51(1-10). <https://doi.org/10.1016/j.atmosenv.2011.11.063>.
85. James P, Stohl A, Forster C, Eckhardt S, Seibert P, A F. A 15-year climatology of stratosphere–troposphere exchange with a Lagrangian particle dispersion model 2. Mean climate and seasonal variability. *J Geophys Res*. 2003;108(D12):8522. <https://doi.org/10.1029/2002jd002639>.
86. Jiang X, Wiedinmyer C, Carlton AG. Aerosols from fires: an examination of the effects on ozone photochemistry in the Western United States. *Environ Sci Technol*. 2012;46(21):11878–86. <https://doi.org/10.1021/es301541k>.
87. Jiang X, 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>.
88. Katragkou E, Zanis P, Kioutsioukis I, Tegoulas I, Melas D, Krüger BC, et al. Future climate change impacts on summer surface ozone from regional climate-air quality simulations over Europe. *J Geophys Res*. 2011;116(D22). <https://doi.org/10.1029/2011jd015899>.
89. 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>.
90. Kawase H, Nagashima T, Sudo K, Nozawa T. Future changes in tropospheric ozone under Representative Concentration Pathways (RCPs). *Geophys Res Lett*. 2011;38(5). <https://doi.org/10.1029/2010gl046402>.
91. Kelly J, Makar PA, Plummer DA. Projections of mid-century summer air-quality for North America: effects of changes in

- climate and precursor emissions. *Atmos Chem Phys*. 2012;12(12): 5367–90. <https://doi.org/10.5194/acp-12-5367-2012>.
92. Kirschke S, Bousquet P, Ciais P, Saunoy M, Canadell JG, Dlugokencky EJ, et al. Three decades of global methane sources and sinks. *Nature Geosci*. 2013;6(10):813–23. <https://doi.org/10.1038/ngeo1955>.
93. Knorr W, Jiang L, Arneth A. Climate, CO₂ and human population impacts on global wildfire emissions. *Biogeosciences*. 2016;13(1):267–82. <https://doi.org/10.5194/bg-13-267-2016>.
94. Koumoutsaris S, Bey I, Generoso S, Thouret V. Influence of El Niño–Southern Oscillation on the interannual variability of tropospheric ozone in the northern midlatitudes. *J Geophys Res*. 2008; 113(D19): doi: <https://doi.org/10.1029/2007jd009753>.
95. Kumar KK. On the weakening relationship between the Indian monsoon and ENSO. *Science*. 1999;284(5423):2156–9. <https://doi.org/10.1126/science.284.5423.2156>.
96. Lal S, Venkataramani S, Srivastava S, Gupta S, Mallik C, Naja M, et al. Transport effects on the vertical distribution of tropospheric ozone over the tropical marine regions surrounding India. *J Geophys Res*. 2013;118(3):1513–24. <https://doi.org/10.1002/jgrd.50180>.
97. Lam YF, Fu JS, Wu S, Mickley LJ. Impacts of future climate change and effects of biogenic emissions on surface ozone and particulate matter concentrations in the United States. *Atmos Chem Phys*. 2011;11(10):4789–806. <https://doi.org/10.5194/acp-11-4789-2011>.
98. Lamarque J-F, Hess PG. Arctic Oscillation modulation of the Northern Hemisphere spring tropospheric ozone. *Geophys Res Lett*. 2004;31(6). <https://doi.org/10.1029/2003gl019116>.
99. Lamarque JF, Shindell DT, Josse B, Young PJ, Cionni I, Eyring V, et al. The Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP): overview and description of models, simulations and climate diagnostics. *Geosci Model Dev*. 2013;6(1):179–206. <https://doi.org/10.5194/gmd-6-179-2013>.
100. Langford AO. Stratosphere-troposphere exchange at the subtropical jet: contribution to the tropospheric ozone budget at midlatitudes. *Geophys Res Lett*. 1999;26(16):2449–52. <https://doi.org/10.1029/1999gl005556>.
101. Langner J, Engardt M, Baklanov A, Christensen JH, Gauss M, Geels C, et al. A multi-model study of impacts of climate change on surface ozone in Europe. *Atmos Chem Phys*. 2012;12(21): 10423–40. <https://doi.org/10.5194/acp-12-10423-2012>.
102. Lawrence MG, Lelieveld J. Atmospheric pollutant outflow from southern Asia: a review. *Atmos Chem Phys*. 2010;10(22):11017–96. <https://doi.org/10.5194/acp-10-11017-2010>.
103. Lehmann J, Coumou D, Frieler K, Eliseev AV, Levermann A. Future changes in extratropical storm tracks and baroclinicity under climate change. *Environ Res Lett*. 2014;9(8):084002. <https://doi.org/10.1088/1748-9326/9/8/084002>.
104. Lei H, Wuebbles DJ, Liang X-Z. Projected risk of high ozone episodes in 2050. *Atmos Environ*. 2012;59:567–77. <https://doi.org/10.1016/j.atmosenv.2012.05.051>.
105. Leibensperger EM, Mickley LJ, Jacob DJ. Sensitivity of US air quality to mid-latitude cyclone frequency and implications of 1980–2006 climate change. *Atmos Chem Phys*. 2008;8(23): 7075–86. <https://doi.org/10.5194/acp-8-7075-2008>.
106. Lelieveld J, Boursoukoudis E, Bruhl C, Fischer H, Fuchs H, Harder H, et al. The South Asian monsoon-pollution pump and purifier. *Science*. 2018. <https://doi.org/10.1126/science.aar2501>.
107. Li S, Wang T, Huang X, Pu X, Li M, Chen P, et al. Impact of east Asian summer monsoon on surface ozone pattern in China. *J Geophys Res*. 2018;123(2):1401–11. <https://doi.org/10.1002/2017jd027190>.
108. Liao H, Chen W-T, Seinfeld JH. Role of climate change in global predictions of future tropospheric ozone and aerosols. *J Geophys Res*. 2006;111(D12). <https://doi.org/10.1029/2005jd006852>.
109. Lin JT, Patten KO, Hayhoe K, Liang XZ, Wuebbles DJ. Effects of future climate and biogenic emissions changes on surface ozone over the United States and China. *J Appl Meteorol Climatol*. 2008;47:1888–909. <https://doi.org/10.1175/2007jamc1681.1>.
110. Lin M, Horowitz LW, Oltmans SJ, Fiore AM, Fan S. Tropospheric ozone trends at Mauna Loa observatory tied to decadal climate variability. *Nat Geosci*. 2014;7(2):136–43. <https://doi.org/10.1038/ngeo2066>.
111. Lin M, 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;6:7105. <https://doi.org/10.1038/ncomms8105>.
112. Liu J, Rodriguez JM, Thompson AM, Logan JA, Douglass AR, Olsen MA, et al. Origins of tropospheric ozone interannual variation over Réunion: a model investigation. *J Geophys Res*. 2016;121(1):521–37. <https://doi.org/10.1002/2015jd023981>.
113. Lombardozzi D, Levis S, Bonan G, Hess PG, Sparks JP. The influence of chronic ozone exposure on global carbon and water cycles. *J Clim*. 2015;28(1):292–305. <https://doi.org/10.1175/jcli-d-14-00223.1>.
114. Lu R, Dong B, Ding H. Impact of the Atlantic Multidecadal Oscillation on the Asian summer monsoon. *Geophys Res Lett*. 2006;33(24). <https://doi.org/10.1029/2006gl027655>.
115. Lu J, Deser C, Reichler T. Cause of the widening of the tropical belt since 1958. *Geophys Res Lett*. 2009;36(3):L03803. <https://doi.org/10.1029/2008gl036076>.
116. Lu X, Zhang L, Yue X, Zhang J, Jaffe DA, Stohl A, et al. Wildfire influences on the variability and trend of summer surface ozone in the mountainous western United States. *Atmos Chem Phys*. 2016;16(22):14687–702. <https://doi.org/10.5194/acp-16-14687-2016>.
117. Lu X, Zhang L, Liu X, Gao M, Zhao Y, Shao J. Lower tropospheric ozone over India and its linkage to the South Asian monsoon. *Atmos Chem Phys*. 2018a;18(5):3101–18. <https://doi.org/10.5194/acp-18-3101-2018>.
118. Lu X, Hong J, Zhang L, Cooper OR, Schultz MG, Xu X, et al. Severe surface ozone pollution in China: a global perspective. *Environ Sci Technol Lett*. 2018b;5(8):487–94. <https://doi.org/10.1021/acs.estlett.8b00366>.
119. Lu X, Zhang L, Chen Y, Zhou M, Zheng B, Li K, et al. Exploring 2016–2017 surface ozone pollution over China: source contributions and meteorological influences. *Atmos Chem Phys*. 2019a;19(12):8339–8361. <https://doi.org/10.5194/acp-19-8339-2019>.
120. Lu X, Zhang L, Zhao Y, Jacob DJ, Hu Y, Hu L, et al. Surface and tropospheric ozone trends in the Southern Hemisphere since 1990: possible linkages to poleward expansion of the Hadley Circulation. *Sci Bull*. 2019b;64(6):400–9. <https://doi.org/10.1016/j.scib.2018.12.021>.
121. Lucas C, Timbal B, Nguyen H. The expanding tropics: a critical assessment of the observational and modeling studies. *Wiley Interdiscip Rev Clim Chang*. 2014;5(1):89–112. <https://doi.org/10.1002/wcc.251>.
122. Meul S, Langematz U, Kröger P, Oberländer-Hayn S, Jöckel 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>.
123. Monks PS, Archibald AT, Colette A, Cooper O, Coyle M, Derwent R, et al. Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer. *Atmos Chem Phys*. 2015;15(15):8889–973. <https://doi.org/10.5194/acp-15-8889-2015>.

124. Morgenstern O, Hegglin MI, Rozanov E, Connor FM, Abraham NL, Akiyoshi H, et al. Review of the global models used within phase 1 of the Chemistry–Climate Model Initiative (CCMI). *Geosci Model Dev*. 2017;10(2):639–71. <https://doi.org/10.5194/gmd-10-639-2017>.
125. 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>.
126. Murray LT, Jacob DJ, Logan JA, Hudman RC, Koshak WJ. Optimized regional and interannual variability of lightning in a global chemical transport model constrained by LIS/OTD satellite data. *J Geophys Res*. 2012;117(D20):D20307. <https://doi.org/10.1029/2012jd017934>.
127. Murray LT, Logan JA, Jacob DJ. Interannual variability in tropical tropospheric ozone and OH: the role of lightning. *J Geophys Res*. 2013;118(19):11,468–411,480. <https://doi.org/10.1002/jgrd.50857>.
128. Myriokefalitakis S, Daskalakis N, Fanourgakis GS, Voulgarakis A, Krol MC, Aan de Brugh JM, et al. Ozone and carbon monoxide budgets over the Eastern Mediterranean. *Sci Total Environ*. 2016;(40–52):563–4. <https://doi.org/10.1016/j.scitotenv.2016.04.061>.
129. Nakicenovic N, Alcamo J, Grubler A, Riahi K, Roehrl RA, Rogner HH, Victor N. Special report on emissions scenarios (SRES), a special report of Working Group III of the intergovernmental panel on climate change. Cambridge University Press; 2000.
130. Nassar R, Logan JA, Megretskaia IA, Murray LT, Zhang L, Jones DBA. Analysis of tropical tropospheric ozone, carbon monoxide, and water vapor during the 2006 El Niño using TES observations and the GEOS-Chem model. *J Geophys Res*. 2009;114(D17). <https://doi.org/10.1029/2009jd011760>.
131. Neu JL, Flury T, Manney GL, Santee ML, Livesey NJ, Worden J. Tropospheric ozone variations governed by changes in stratospheric circulation. *Nat Geosci*. 2014;7(5):340–4. <https://doi.org/10.1038/ngeo2138>.
132. Nolte CG, Spero TL, Bowden JH, Mallard MS, Dolwick PD. The potential effects of climate change on air quality across the conterminous U.S. at 2030 under three Representative Concentration Pathways (RCPs). *Atmos Chem Phys*. 2018;18(20):15471–15489. <https://doi.org/10.5194/acp-2018-510>.
133. Nowack PJ, Braesicke P, Luke Abraham N, Pyle JA. On the role of ozone feedback in the ENSO amplitude response under global warming. *Geophys Res Lett*. 2017;44(8):3858–66. <https://doi.org/10.1002/2016gl072418>.
134. O'Connor FM, Boucher O, Gedney N, Jones CD, Folberth GA, Coppel R, et al. Possible role of wetlands, permafrost, and methane hydrates in the methane cycle under future climate change: a review. *Rev Geophys*. 2010;48(4). <https://doi.org/10.1029/2010rg000326>.
135. Ojha N, Naja M, Singh KP, Sarangi T, Kumar R, Lal S, et al. Variabilities in ozone at a semi-urban site in the Indo-Gangetic Plain region: association with the meteorology and regional processes. *J Geophys Res*. 2012;117(D20):D20301. <https://doi.org/10.1029/2012jd017716>.
136. 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>.
137. Oman LD, Ziemke JR, Douglass AR, Waugh DW, Lang C, Rodriguez JM, et al. The response of tropical tropospheric ozone to ENSO. *Geophys Res Lett*. 2011;38(13):L13706. <https://doi.org/10.1029/2011gl047865>.
138. Oman LD, Douglass AR, Ziemke JR, Rodriguez JM, Waugh DW, Nielsen JE. The ozone response to ENSO in Aura satellite measurements and a chemistry-climate simulation. *J Geophys Res*. 2013;118(2):965–76. <https://doi.org/10.1029/2012jd018546>.
139. Ordóñez C, Brunner D, Staehelin J, Hadjinicolaou P, Pyle JA, Jonas M, et al. Strong influence of lowermost stratospheric ozone on lower tropospheric background ozone changes over Europe. *Geophys Res Lett*. 2007;34(7). <https://doi.org/10.1029/2006gl029113>.
140. Ordóñez C, Barriopedro D, García-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>.
141. Parrington M, Palmer PI, Lewis AC, Lee JD, Rickard AR, Di Carlo P, et al. Ozone photochemistry in boreal biomass burning plumes. *Atmos Chem Phys*. 2013;13(15):7321–41. <https://doi.org/10.5194/acp-13-7321-2013>.
142. Paulot F, Henze DK, Wennberg PO. Impact of the isoprene photochemical cascade on tropical ozone. *Atmos Chem Phys*. 2012;12(3):1307–25. <https://doi.org/10.5194/acp-12-1307-2012>.
143. Pausata FSR, Pozzoli L, Vignati E, Dentener FJ. North Atlantic Oscillation and tropospheric ozone variability in Europe: model analysis and measurements intercomparison. *Atmos Chem Phys*. 2012;12(14):6357–76. <https://doi.org/10.5194/acp-12-6357-2012>.
144. Pegoraro E, Rey A, Greenberg J, Harley P, Grace J, Malhi Y, et al. Effect of drought on isoprene emission rates from leaves of *Quercus virginiana* Mill. *Atmos Environ*. 2004;38(36):6149–56. <https://doi.org/10.1016/j.atmosenv.2004.07.028>.
145. Penrod A, Zhang Y, Wang K, Wu S-Y, Leung LR. Impacts of future climate and emission changes on U.S. air quality. *Atmos Environ*. 2014;89:533–47. <https://doi.org/10.1016/j.atmosenv.2014.01.001>.
146. Pfister GG, Walters S, Lamarque JF, Fast J, Barth MC, Wong J, et al. Projections of future summertime ozone over the U.S. *J Geophys Res*. 2014;119(9):5559–82. <https://doi.org/10.1002/2013jd020932>.
147. 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):124004. <https://doi.org/10.1088/1748-9326/11/12/124004>.
148. Potosnak MJ, LeSturgeon L, Pallardy SG, Hosman KP, Gu L, Karl T, et al. Observed and modeled ecosystem isoprene fluxes from an oak-dominated temperate forest and the influence of drought stress. *Atmos Environ*. 2014;84:314–22. <https://doi.org/10.1016/j.atmosenv.2013.11.055>.
149. Price C, Rind D. A simple lightning parameterization for calculating global lightning distributions. *J Geophys Res*. 1992;97(D9):9919–33. <https://doi.org/10.1029/92jd00719>.
150. Pusede SE, Steiner AL, Cohen RC. Temperature and recent trends in the chemistry of continental surface ozone. *Chem Rev*. 2015;115(10):3898–918. <https://doi.org/10.1021/cr5006815>.
151. 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*. 2015;120(2):784–800. <https://doi.org/10.1002/2014jd022303>.
152. 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>.
153. Ruppel CD, Kessler JD. The interaction of climate change and methane hydrates. *Rev Geophys*. 2017;55(1):126–68. <https://doi.org/10.1002/2016rg000534>.
154. Safieddine S, Boynard A, Coheur PF, Hurtmans D, Pfister G, Quennehen B, et al. Summertime tropospheric ozone assessment over the Mediterranean region using the thermal infrared IASI/

- MetOp sounder and the WRF-Chem model. *Atmos Chem Phys*. 2014;14(18):10119–31. <https://doi.org/10.5194/acp-14-10119-2014>.
155. Safieddine S, Boynard A, Hao N, Huang F, Wang L, Ji D, et al. Tropospheric ozone variability during the East Asian summer monsoon as observed by satellite (IASI), aircraft (MOZAIC) and ground stations. *Atmos Chem Phys*. 2016;16(16):10489–500. <https://doi.org/10.5194/acp-16-10489-2016>.
 156. Sahu LK, Sheel V, Kajino M, Deushi M, Gunthe SS, Sinha PR, et al. Seasonal and interannual variability of tropospheric ozone over an urban site in India: a study based on MOZAIC and CCM vertical profiles over Hyderabad. *J Geophys Res*. 2014;119(6):3615–41. <https://doi.org/10.1002/2013jd021215>.
 157. Sandeep S, Ajayamohan RS, Boos WR, Sabin TP, Praveen V. Decline and poleward shift in Indian summer monsoon synoptic activity in a warming climate. *Proc Natl Acad Sci U S A*. 2018;115(11):2681–6. <https://doi.org/10.1073/pnas.1709031115>.
 158. Sanderson MG, Jones CD, Collins WJ, Johnson CE, Derwent RG. Effect of climate change on isoprene emissions and surface ozone levels. *Geophys Res Lett*. 2003;30(18). <https://doi.org/10.1029/2003gl017642>.
 159. Saunio M, Bousquet P, Poulter B, Peregon A, Ciais P, Canadell JG, et al. The global methane budget 2000–2012. *Earth Syst Sci Data*. 2016;8(2):697–751. <https://doi.org/10.5194/essd-8-697-2016>.
 160. Schindlbacher A. Effects of soil moisture and temperature on NO, NO₂, and N₂O emissions from European forest soils. *J Geophys Res*. 2004;109(D17). <https://doi.org/10.1029/2004jd004590>.
 161. Schnell JL, Prather MJ. Co-occurrence of extremes in surface ozone, particulate matter, and temperature over eastern North America. *Proc Natl Acad Sci U S A*. 2017;114(11):2854–9. <https://doi.org/10.1073/pnas.1614453114>.
 162. 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>.
 163. Schumann U, Huntrieser H. The global lightning-induced nitrogen oxides source. *Atmos Chem Phys*. 2007;7(14):3823–907. <https://doi.org/10.5194/acp-7-3823-2007>.
 164. Seinfeld JH, Pandis SN. *Atmospheric chemistry and physics: from air pollution to climate change*. Hoboken: Wiley; 2012.
 165. Sekiya T, Sudo K. Role of meteorological variability in global tropospheric ozone during 1970–2008. *J Geophys Res*. 2012;117(D18). <https://doi.org/10.1029/2012jd018054>.
 166. Shapiro MA, Wernli H, Bond NA, Langland R. The influence of the 1997–99 El Niño Southern Oscillation on extratropical baroclinic life cycles over the eastern North Pacific. *Q J R Meteorol Soc*. 2001;127(572):331–42. <https://doi.org/10.1002/qj.49712757205>.
 167. Shaw TA, Baldwin M, Barnes EA, Caballero R, Garfinkel CI, Hwang YT, et al. Storm track processes and the opposing influences of climate change. *Nat Geosci*. 2016;9(9):656–64. <https://doi.org/10.1038/ngeo2783>.
 168. Shea RW, Shea BW, Kauffman JB, Ward DE, Haskins CI, Scholes MC. Fuel biomass and combustion factors associated with fires in savanna ecosystems of South Africa and Zambia. *J Geophys Res*. 1996;101(D19):23551–68. <https://doi.org/10.1029/95jd02047>.
 169. Shen L, Mickley LJ. Effects of El Niño on summertime ozone air quality in the eastern United States. *Geophys Res Lett*. 2017a;44(24):12543–50. <https://doi.org/10.1002/2017GL076150>.
 170. Shen L, Mickley LJ. Seasonal prediction of US summertime ozone using statistical analysis of large scale climate patterns. *Proc Natl Acad Sci U S A*. 2017b. <https://doi.org/10.1073/pnas.1610708114>.
 171. Shen L, Mickley LJ, Tai APK. 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>.
 172. Shen L, Mickley LJ, Gilleland E. Impact of increasing heat waves on U.S. ozone episodes in the 2050s: results from a multimodel analysis using extreme value theory. *Geophys Res Lett*. 2016;43(8):4017–25. <https://doi.org/10.1002/2016GL068432>.
 173. Shen L, Mickley LJ, Leibensperger EM, Li M. Strong dependence of U.S. summertime air quality on the decadal variability of Atlantic Sea surface temperatures. *Geophys Res Lett*. 2017;44(24):12527–35. <https://doi.org/10.1002/2017GL075905>.
 174. Shindell DT, Walter BP, Faluvegi G. Impacts of climate change on methane emissions from wetlands. *Geophys Res Lett*. 2004;31(21). <https://doi.org/10.1029/2004gl021009>.
 175. Shindell DT, Lamarque JF, Schulz M, Flanner M, Jiao C, Chin M, et al. Radiative forcing in the ACCMIP historical and future climate simulations. *Atmos Chem Phys*. 2013;13(6):2939–74. <https://doi.org/10.5194/acp-13-2939-2013>.
 176. Siegert F, Ruecker G, Hinrichs A, Hoffmann AA. Increased damage from fires in logged forests during droughts caused by El Niño. *Nature*. 2001;414(6862):437–40. <https://doi.org/10.1038/35106547>.
 177. Sitch S, Cox PM, Collins WJ, Huntingford C. Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. *Nature*. 2007;448(7155):791–4. <https://doi.org/10.1038/nature06059>.
 178. Škerlak B, Sprenger M, Wernli H. A global climatology of stratosphere–troposphere exchange using the ERA-Interim data set from 1979 to 2011. *Atmos Chem Phys*. 2014;14(2):913–37. <https://doi.org/10.5194/acp-14-913-2014>.
 179. Solberg S, Hov Ø, Søvde A, Isaksen ISA, Coddeville P, De Backer H, et al. European surface ozone in the extreme summer 2003. *J Geophys Res*. 2008;(D7):113. <https://doi.org/10.1029/2007jd009098>.
 180. Solomon S, Ivy DJ, Kinnison D, Mills MJ, Neely RR 3rd, Schmidt A. Emergence of healing in the Antarctic ozone layer. *Science*. 2016;353(6296):269–74. <https://doi.org/10.1126/science.aae0061>.
 181. Spracklen DV, Mickley LJ, Logan JA, Hudman RC, Yevich R, Flannigan MD, et al. Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. *J Geophys Res*. 2009;114(D20). <https://doi.org/10.1029/2008jd010966>.
 182. 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>.
 183. 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>.
 184. Stevenson DS, Young PJ, Naik V, Lamarque JF, Shindell DT, Voulgarakis A, et al. Tropospheric ozone changes, radiative forcing and attribution to emissions in the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP). *Atmos Chem Phys*. 2013;13(6):3063–85. <https://doi.org/10.5194/acp-13-3063-2013>.
 185. Stohl A, Bonasoni P, Cristofanelli P, Collins W, Feichter J, Frank A, et al. Stratosphere–troposphere exchange: a review, and what we have learned from STACCATO. *J Geophys Res-Atmos*. 2003;108(D12):8516. <https://doi.org/10.1029/2002jd002490>.
 186. Stroe A, Rodriguez JM, Logan JA, Cooper OR, Witte JC, Lamsal LN, et al. Trends and variability in surface ozone over the United States. *J Geophys Res-Atmos*. 2015;120(17):9020–42. <https://doi.org/10.1002/2014jd022784>.

187. Sudo K, Takahashi M, Akimoto H. Future changes in stratosphere-troposphere exchange and their impacts on future tropospheric ozone simulations. *Geophys Res Lett*. 2003;30(24). <https://doi.org/10.1029/2003gl018526>.
188. Sun W, Hess P, Liu C. The impact of meteorological persistence on the distribution and extremes of ozone. *Geophys Res Lett*. 2017. <https://doi.org/10.1002/2016gl071731>.
189. Sutton RT, Hodson DL. Atlantic Ocean forcing of North American and European summer climate. *Science*. 2005;309(5731):115–8. <https://doi.org/10.1126/science.1109496>.
190. Sutton RT, Hodson DLR. Climate response to basin-scale warming and cooling of the North Atlantic Ocean. *J Clim*. 2007;20(5):891–907. <https://doi.org/10.1175/jcli4038.1>.
191. Tai APK, Mickley LJ, Heald CL, Wu S. 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>.
192. Talukdar RK, Burkholder JB, Schmoltner A-M, Roberts JM, Wilson RR, Ravishankara AR. Investigation of the loss processes for peroxyacetyl nitrate in the atmosphere: UV photolysis and reaction with OH. *J Geophys Res*. 1995;100(D7):14163. <https://doi.org/10.1029/95jd00545>.
193. Tang Q, Prather MJ, Hsu J. Stratosphere-troposphere exchange ozone flux related to deep convection. *Geophys Res Lett*. 2011;38(3). <https://doi.org/10.1029/2010gl046039>.
194. Tao L, Hu Y, Liu J. Anthropogenic forcing on the Hadley circulation in CMIP5 simulations. *Clim Dyn*. 2015;46(9–10):3337–50. <https://doi.org/10.1007/s00382-015-2772-1>.
195. Terao Y, Logan JA, Douglass AR, Stolarski RS. Contribution of stratospheric ozone to the interannual variability of tropospheric ozone in the northern extratropics. *J Geophys Res*. 2008;113(D18). <https://doi.org/10.1029/2008jd009854>.
196. The Royal Society. Ground-level ozone in the 21st century: future trends, impacts and policy implications. Royal Society Science Policy Report. 2008;15(08).
197. Turner AJ, Fiore AM, Horowitz LW, Bauer M. Summertime cyclones over the Great Lakes Storm Track from 1860–2100: variability, trends, and association with ozone pollution. *Atmos Chem Phys*. 2013;13(2):565–78. <https://doi.org/10.5194/acp-13-565-2013>.
198. Tyrllis E, Škerlak B, Sprenger M, Wernli H, Zittis G, Lelieveld J. On the linkage between the Asian summer monsoon and tropopause fold activity over the eastern Mediterranean and the Middle East. *J Geophys Res*. 2014;119(6):3202–21. <https://doi.org/10.1002/2013jd021113>.
199. Unger N, Shindell DT, Koch DM, Amann M, Cofala J, Streets DG. Influences of man-made emissions and climate changes on tropospheric ozone, methane, and sulfate at 2030 from a broad range of possible futures. *J Geophys Res*. 2006;111(D12). <https://doi.org/10.1029/2005jd006518>.
200. Val Martin M, Logan JA, Kahn RA, Leung FY, Nelson DL, Diner DJ. Smoke injection heights from fires in North America: analysis of 5 years of satellite observations. *Atmos Chem Phys*. 2010;10(4):1491–510. <https://doi.org/10.5194/acp-10-1491-2010>.
201. 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>.
202. van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, et al. The representative concentration pathways: an overview. *Clim Chang*. 2011;109(1–2):5–31. <https://doi.org/10.1007/s10584-011-0148-z>.
203. Veira A, Lasslop G, Kloster S. Wildfires in a warmer climate: emission fluxes, emission heights, and black carbon concentrations in 2090–2099. *J Geophys Res*. 2016;121(7):3195–223. <https://doi.org/10.1002/2015jd024142>.
204. Vinken GCM, Boersma KF, Maasakkers JD, Adon M, Martin RV. Worldwide biogenic soil NO_x emissions inferred from OMI NO₂ observations. *Atmos Chem Phys*. 2014;14(18):10363–81. <https://doi.org/10.5194/acp-14-10363-2014>.
205. von Schneidmesser 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>.
206. Wang B, Ding Q. Global monsoon: dominant mode of annual variation in the tropics. *Dyn Atmos Oceans*. 2008;44(3–4):165–83. <https://doi.org/10.1016/j.dynatmoce.2007.05.002>.
207. Wang T, Wei XL, Ding AJ, Poon CN, Lam KS, Li YS, et al. Increasing surface ozone concentrations in the background atmosphere of Southern China, 1994–2007. *Atmos Chem Phys*. 2009;9(16):6217–27. <https://doi.org/10.5194/acp-9-6217-2009>.
208. Wang Y, Shen L, Wu S, Mickley L, He J, Hao J. Sensitivity of surface ozone over China to 2000–2050 global changes of climate and emissions. *Atmos Environ*. 2013;75:374–82. <https://doi.org/10.1016/j.atmosenv.2013.04.045>.
209. Wang Y, Jia B, Wang S-C, Estes M, Shen L, Xie Y. 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>.
210. Wang T, Xue L, Brimblecombe P, Lam YF, Li L, Zhang L. Ozone pollution in China: a review of concentrations, meteorological influences, chemical precursors, and effects. *Sci Total Environ*. 2017;575:1582–96. <https://doi.org/10.1016/j.scitotenv.2016.10.081>.
211. Watson L, Lacrosonnière G, Gauss M, Engardt M, Andersson C, Josse B, et al. Impact of emissions and +2 °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>.
212. Weaver CP, Cooter E, Gilliam R, Gilliland A, Grambsch A, Grano D, et al. A preliminary synthesis of modeled climate change impacts on U.S. regional ozone concentrations. *Bull Am Meteorol Soc*. 2009;90(12):1843–63. <https://doi.org/10.1175/2009bams2568.1>.
213. Wesely ML. Parameterization of surface resistances to gaseous dry deposition in regional-scale numerical-models. *Atmos Environ*. 1989;23(6):1293–304. [https://doi.org/10.1016/0004-6981\(89\)90153-4](https://doi.org/10.1016/0004-6981(89)90153-4).
214. Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW. Warming and earlier spring increase western U.S. forest wildfire activity. *Science*. 2006;313(5789):940–3. <https://doi.org/10.1126/science.1128834>.
215. Wik M, Varner RK, Anthony KW, MacIntyre S, Bastviken D. Climate-sensitive northern lakes and ponds are critical components of methane release. *Nat Geosci*. 2016;9(2):99–105. <https://doi.org/10.1038/ngeo2578>.
216. Wu S, Mickley LJ, Jacob DJ, Logan JA, Yantosca RM, Rind D. Why are there large differences between models in global budgets of tropospheric ozone? *J Geophys Res*. 2007;112(D5). <https://doi.org/10.1029/2006jd007801>.
217. Wu S, Mickley LJ, Leibensperger EM, Jacob DJ, Rind D, Streets DG. Effects of 2000–2050 global change on ozone air quality in the United States. *J Geophys Res*. 2008;113(D6). <https://doi.org/10.1029/2007jd008917>.
218. Wu S, Mickley LJ, Kaplan JO, Jacob DJ. Impacts of changes in land use and land cover on atmospheric chemistry and air quality

- over the 21st century. *Atmos Chem Phys*. 2012;12(3):1597–609. <https://doi.org/10.5194/acp-12-1597-2012>.
219. Xie Y, Paulot F, Carter WPL, Nolte CG, Luecken DJ, Hutzell WT, et al. Understanding the impact of recent advances in isoprene photo-oxidation on simulations of regional air quality. *Atmos Chem Phys*. 2013;13(16):8439–55. <https://doi.org/10.5194/acp-13-8439-2013>.
 220. Xu L, Yu J-Y, Schnell JL, Prather MJ. The seasonality and geographic dependence of ENSO impacts on U.S. surface ozone variability. *Geophys. Res. Lett.* 2017;44(7):3420–8. <https://doi.org/10.1002/2017gl073044>.
 221. Xu W, Xu X, Lin M, Lin W, Tarasick D, Tang J, et al. Long-term trends of surface ozone and its influencing factors at the Mt Waliguan GAW station, China – part 2: the roles of anthropogenic emissions and climate variability. *Atmos Chem Phys*. 2018;18(2):773–98. <https://doi.org/10.5194/acp-18-773-2018>.
 222. Yan X, Ohara T, Akimoto H. Statistical modeling of global soil NO_x emissions. *Glob Biogeochem Cycles*. 2005;19(3). <https://doi.org/10.1029/2004gb002276>.
 223. Yan Y, Lin J, He C. Ozone trends over the United States at different times of day. *Atmos Chem Phys*. 2018;18(2):1185–202. <https://doi.org/10.5194/acp-18-1185-2018>.
 224. Yang Y, Liao H, Li J. Impacts of the East Asian summer monsoon on interannual variations of summertime surface-layer ozone concentrations over China. *Atmos Chem Phys*. 2014;14(13):6867–79. <https://doi.org/10.5194/acp-14-6867-2014>.
 225. Yi K, Liu J, Ban-Weiss G, Zhang J, Tao W, Cheng Y, 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>.
 226. Yienger JJ, Levy H. Empirical model of global soil-biogenic NO_x emissions. *J Geophys Res*. 1995;100(D6):11447. <https://doi.org/10.1029/95jd00370>.
 227. Yin JH. A consistent poleward shift of the storm tracks in simulations of 21st century climate. *Geophys Res Lett.* 2005;32(18):L18701. <https://doi.org/10.1029/2005gl023684>.
 228. Young PJ, Arneth A, Schurgers G, Zeng G, Pyle JA. The CO₂ inhibition of terrestrial isoprene emission significantly affects future ozone projections. *Atmos Chem Phys*. 2009;9(8):2793–803. <https://doi.org/10.5194/acp-9-2793-2009>.
 229. Young PJ, Archibald AT, Bowman KW, Lamarque JF, Naik V, Stevenson DS, et al. Pre-industrial to end 21st century projections of tropospheric ozone from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP). *Atmos Chem Phys*. 2013;13(4):2063–90. <https://doi.org/10.5194/acp-13-2063-2013>.
 230. Yue X, Mickley LJ, Logan JA, Kaplan JO. Ensemble projections of wildfire activity and carbonaceous aerosol concentrations over the western United States in the mid-21st century. *Atmos Environ* (1994). 2013;77:767–80. <https://doi.org/10.1016/j.atmosenv.2013.06.003>.
 231. Yue X, Unger N, Harper K, Xia X, Liao H, Zhu T, et al. Ozone and haze pollution weakens net primary productivity in China. *Atmos Chem Phys*. 2017;17(9):6073–89. <https://doi.org/10.5194/acp-17-6073-2017>.
 232. Zanis P, Hadjinicolaou P, Pozzer A, Tyrllis E, Dafka S, Mihalopoulos N, et al. Summertime free-tropospheric ozone pool over the eastern Mediterranean/Middle East. *Atmos Chem Phys*. 2014;14(1):115–32. <https://doi.org/10.5194/acp-14-115-2014>.
 233. Zeng G, Pyle J. Influence of El Niño Southern Oscillation on stratosphere/troposphere exchange and the global tropospheric ozone budget. *Geophys Res Lett.* 2005;32(1). <https://doi.org/10.1029/2004gl021353>.
 234. Zeng G, Morgenstern O, Braesicke P, Pyle JA. Impact of stratospheric ozone recovery on tropospheric ozone and its budget. *Geophys Res Lett.* 2010;37(9). <https://doi.org/10.1029/2010gl042812>.
 235. Zhang Y, Wang Y. 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>.
 236. Zhang L, Jacob DJ, Boersma KF, Jaffe DA, Olson JR, Bowman KW, et al. Transpacific transport of ozone pollution and the effect of recent Asian emission increases on air quality in North America: an integrated analysis using satellite, aircraft, ozonesonde, and surface observations. *Atmos Chem Phys*. 2008;8(20):6117–36. <https://doi.org/10.5194/acp-8-6117-2008>.
 237. Zhang L, Li QB, Jin J, Liu H, Livesey N, Jiang JH, et al. Impacts of 2006 Indonesian fires and dynamics on tropical upper tropospheric carbon monoxide and ozone. *Atmos Chem Phys*. 2011;11(21):10929–46. <https://doi.org/10.5194/acp-11-10929-2011>.
 238. Zhang L, Jacob DJ, Yue X, Downey NV, Wood DA, Blewitt D. Sources contributing to background surface ozone in the US intermountain West. *Atmos Chem Phys*. 2014;14(11):5295–309. <https://doi.org/10.5194/acp-14-5295-2014>.
 239. Zhao Z, Wang Y. Influence of the West Pacific subtropical high on surface ozone daily variability in summertime over eastern China. *Atmos Environ*. 2017;170:197–204. <https://doi.org/10.1016/j.atmosenv.2017.09.024>.
 240. Zhao C, Wang Y, Yang Q, Fu R, Cunnold D, Choi Y. Impact of East Asian summer monsoon on the air quality over China: view from space. *J Geophys Res*. 2010;115(D9). <https://doi.org/10.1029/2009jd012745>.
 241. Zhao Y, Zhang L, Zhou M, Chen D, Lu X, Tao W, Liu J, Tian H, Ma Y, Fu T-M. Influences of planetary boundary layer mixing parameterization on summertime surface ozone concentration and dry deposition over North China. submitted to *Atmospheric Environment*.
 242. Zhou D, Ding A, Mao H, Fu C, Wang T, Chan LY, et al. Impacts of the East Asian monsoon on lower tropospheric ozone over coastal South China. *Environ Res Lett.* 2013;8(4):044011. <https://doi.org/10.1088/1748-9326/8/4/044011>.
 243. Zhou P, Ganzeveld L, Rannik Ü, Zhou L, Gierens R, Taipale D, et al. Simulating ozone dry deposition at a boreal forest with a multi-layer canopy deposition model. *Atmos Chem Phys*. 2017;17(2):1361–79. <https://doi.org/10.5194/acp-17-1361-2017>.
 244. Zhu J, Liang X-Z. Impacts of the Bermuda high on regional climate and ozone over the United States. *J Clim*. 2013;26(3):1018–32. <https://doi.org/10.1175/jcli-d-12-00168.1>.
 245. Zhu Q, Peng C, Ciais P, Jiang H, Liu J, Bousquet P, et al. Interannual variation in methane emissions from tropical wetlands triggered by repeated El Niño Southern Oscillation. *Glob Chang Biol*. 2017;23(11):4706–16. <https://doi.org/10.1111/gcb.13726>.
 246. Zhu L, Val Martin M, Gatti LV, Kahn R, Hecobian A, Fischer EV. Development and implementation of a new biomass burning emissions injection height scheme (BBEIH v1.0) for the GEOS-Chem model (v9-01-01). *Geosci Model Dev*. 2018;11(10):4103–16. <https://doi.org/10.5194/gmd-11-4103-2018>.
 247. Ziemke JR, Chandra S. La Nina and El Nino—induced variabilities of ozone in the tropical lower atmosphere during 1970–2001. *Geophys Res Lett.* 2003;30(3). <https://doi.org/10.1029/2002gl016387>.
 248. Ziemke JR, Chandra S, Oman LD, Bhartia PK. A new ENSO index derived from satellite measurements of column ozone. *Atmos Chem Phys*. 2010;10(8):3711–21. <https://doi.org/10.5194/acp-10-3711-2010>.