



Impact of heatwaves on sources and transformations of ambient volatile organic compounds

Wenqi Liu^{a, #}, Jin Wang^{a, #}, Baoshuang Liu^{a*}, Litao Wang^b, Shaojie Song^{a*}, Yinchang Feng^a

5 ^aKey Laboratory of Urban Air Particulate Pollution Prevention and Control of Ministry of Ecology and Environment, College of Environmental Science and Engineering, Nankai University, Tianjin 300350, China

^bSchool of Environmental Science and Engineering, Hebei University of Science and Technology, Shijiazhuang 050018, China

10 [#] These authors contributed equally

* Corresponding author: Baoshuang Liu, nklbs@nankai.edu.cn; Shaojie Song: songs@nankai.edu.cn

Abstract

Heatwaves are increasingly frequent, intense, and prolonged under climate change, affecting
15 atmospheric chemistry and secondary air pollution. Volatile organic compounds (VOCs) are key precursors of ozone (O₃) and secondary organic aerosol (SOA), yet the impacts of heatwaves on VOC-related processes remain not fully integrated. This review synthesizes advances in heatwave impacts on VOC emissions, source contributions, transformation, and secondary pollution. Based on 287 publications (~67% from 2020-2026), observations show that heatwaves increase total ambient VOCs,
20 but dominant compounds vary by city and reflect local emissions. Temperature-sensitive anthropogenic sources (solvent use, volatile chemical products, fuel storage, vehicle evaporation) increase strongly, whereas combustion sources are less temperature-dependent. Biogenic VOC emissions, especially isoprene and monoterpenes, respond nonlinearly to temperature and are modulated by plant physiology, water stress, and species-specific storage/synthesis. Heatwaves also
25 enhance atmospheric oxidation through increased photolysis and radical production, altering VOC oxidation, radical cycling, O₃ formation regimes, and gas-particle partitioning. Enhanced emissions and oxidation can promote O₃ and SOA formation, but net responses depend on VOC-NO_x sensitivity, peroxyacetyl nitrate (PAN) chemistry, product volatility, partitioning, reactive uptake, and particle-phase diffusion. Observations, experiments, emission parameterizations, source apportionment,
30 inverse modeling, and chemical transport models provide complementary evidence, but uncertainties



remain in temperature-dependent emissions, semi-volatile/intermediate-volatility organic compounds (S/IVOCs) oxidation, multiphase chemistry, and observational constraints. Future research should integrate high-resolution measurements, source apportionment, inverse modeling, and process-based models across heatwave events to quantify source-specific temperature responses and improve
35 predictions of VOC-driven secondary pollution.

Keywords: Heatwaves; Volatile organic compounds; Ozone formation; Secondary organic aerosol; Atmospheric processes



40 1 Introduction

Although substantial progress has been made in reducing primary pollutants in many regions (Chen et al., 2024a; Jiang et al., 2018; Tsimpidi et al., 2025), secondary pollution, particularly ozone (O_3) and secondary organic aerosol (SOA), remains a major challenge in air pollution control worldwide (Chace et al., 2025; Chen et al., 2024d; Li et al., 2019; Nie et al., 2022; Tudor, 2022). Volatile organic
45 compounds (VOCs), as key precursors of O_3 and SOA, govern atmospheric oxidation capacity and the formation of secondary pollutants (Liu et al., 2026b; Monks et al., 2009; Wang et al., 2024e). This challenge is further compounded by the increased frequency and intensity of heatwave events that can substantially alter VOC emissions, atmospheric oxidation processes, and the subsequent evolution of pollutants (Li et al., 2025c; Pfannerstill et al., 2024; Wang et al., 2026g; Xian et al., 2026).

50 Recent studies have increasingly revealed that these heatwave-induced changes extend well beyond temperature-dependent emission responses, involving complex interactions across sources, chemistry, and secondary pollution that remain poorly quantified (Aas et al., 2026; Qin et al., 2025; Wu et al., 2024). For anthropogenic VOCs (AVOCs), studies have highlighted enhanced volatilization from volatile chemical products (VCPs), fuel-related sources, and solvent use under extreme heat, which
55 markedly reshapes urban VOC composition and reactivity during heatwave events (Huang et al., 2022; Rubin et al., 2006; Tan et al., 2021; Wang et al., 2021b; Xian et al., 2026). For biogenic VOCs (BVOCs), studies have increasingly focused on the nonlinear temperature responses of vegetation emissions, particularly for highly reactive species such as isoprene and monoterpenes (Bourtsoukidis et al., 2024, 2025; Seco et al., 2022; Wang et al., 2026d; Zeng et al., 2025). Extending beyond emission responses,
60 studies have also explored how heatwaves influence VOC atmospheric chemistry, particularly through altered oxidative capacity, radical cycling, and precursor-oxidant coupling (Kong et al., 2025; Wang et al., 2026e, g; Zhang et al., 2024c). Furthermore, recent work has highlighted heatwave-induced perturbations in hydroxyl (OH) /HOx (OH+HO₂) radical cycling, peroxyacetyl nitrate (PAN) thermal decomposition, O_3 formation regimes, and the multiphase processes controlling SOA formation and
65 persistence (Li et al., 2024; Wang et al., 2026f; Yang et al., 2026b; Zhang et al., 2024a). A further line of research has sought to isolate the direct thermal effects from concurrent changes in radiation, humidity, boundary layer dynamics, and regional transport (Pan et al., 2026; Wang et al., 2021a; Zhou et al., 2025).



Despite substantial progress in recent years, an integrated understanding of heatwave impacts on VOC-
70 related atmospheric processes remains limited. The responses of VOC emissions, source contributions,
atmospheric oxidation, and secondary pollutant formation are closely coupled, yet they exhibit marked
variability across different emission sources, chemical species, and environmental conditions (Wang
et al., 2026g; Wu et al., 2024; Xian et al., 2026). Recent reviews have addressed several facets of this
nexus from different perspectives. Shan et al. (2025) systematically synthesized the definitions,
75 classifications, long-term trends, and regional characteristics of heatwaves, and assessed their impacts
on air pollution and human health, underscoring the strong temperature dependence of O₃ pollution
and the potential suppression of O₃ enhancement under extreme heatwave. Yang et al. (2026a) focused
on the temperature dependence of BVOC emissions in China, reviewing the physiological and
environmental controls of major BVOC species, particularly isoprene and monoterpenes, as well as
80 the approaches used to characterize and parameterize their temperature responses and the consequent
implications for air quality. Other recent global reviews have examined the broader associations
between intensified heatwaves and air quality, emphasizing the roles of meteorological conditions,
photochemical processes, atmospheric stagnation, and compound climate extremes in modulating O₃
and particulate pollution (Wang et al., 2026c). Overall, these studies have considerably enriched our
85 understanding of the discrete components within the heatwave-VOC-air quality framework. However,
a comprehensive synthesis that connects heatwave-induced changes in VOC emissions and source
contributions with subsequent atmospheric transformation processes and secondary pollutant
formation remains limited.

In this review, we summarize recent advances in understanding the impacts of heatwaves on VOC-
90 related atmospheric processes, with particular emphasis on emission responses, source variations, and
atmospheric transformation mechanisms. Specifically, (i) summarize the definitions, characteristics,
and recent trends of heatwave events to provide the climatic context for investigating heatwave-driven
changes in atmospheric chemistry; (ii) characteristics of ambient VOC species under heatwaves; (iii)
critically assess the methodological approaches used to quantify heatwave impacts on VOC emissions;
95 and (iv) review the mechanisms through which heatwaves influence VOC atmospheric transformation,
with a focus on VOC-to-O₃ and VOC-to-SOA pathways, covering their impacts on atmospheric
oxidative capacity, O₃ formation regime, gas-particle partitioning, and multiphase chemistry. This



review offers a systematic framework for understanding how heatwaves modulate VOC-driven secondary pollution formation, clarifies the complex interactions among temperature-driven emissions, atmospheric chemistry, and physicochemical processes, and highlights key knowledge gaps requiring further investigation under a changing climate.

2 Methods

This study conducted a comprehensive literature search using major academic databases, including ScienceDirect (Elsevier), Web of Science, ACS Publications, and Wiley Online Library. The search strategy employed keywords such as volatile organic compounds (VOC), heatwaves, high temperature, ozone/O₃ pollution, atmospheric transformation mechanisms, source apportionment/analysis methods (e.g., PMF), and temperature-dependent emissions. Relevant publications were systematically reviewed, with particular emphasis on the key processes associated with enhanced VOC emissions under high-temperature heatwaves. A total of 287 papers were reviewed in this work, of which 191 were published from 2020 to 2026, accounting for ~67% of the total, while 113 were published between 2024 and 2026, accounting for ~39%. Literature covered multiple regions, with studies concentrated mainly in China, the United States, and Europe, alongside a number of global-scale studies.

3 Definitions of heatwaves

Currently, there is no globally agreed standard for heatwave definition, and substantial discrepancies persist among the criteria employed by international organizations, countries, and regions (Bunting et al., 2024; Marx et al., 2021; Perkins-Kirkpatrick and Lewis, 2020). Existing approaches to heatwave definition can generally be divided into two categories (Wang et al., 2026i). The first relies on relative climatic thresholds, defining heatwave events based on historical statistical percentiles derived from long-term regional observations, an approach widely adopted in the United States and by major international meteorological agencies (Fischer and Schär, 2010; Hirsch et al., 2019; Perkins and Alexander, 2013; Russo et al., 2015; Smith et al., 2013). The second, in contrast, employs fixed absolute thresholds, using predetermined temperature thresholds and minimum duration criteria to identify heatwave events. In China, one heatwave is defined as a period of at least three consecutive days with daily maximum temperatures reaching 35°C or above (Jiang et al., 2019; Yang et al., 2019),



whereas in many Europe countries, thresholds are often set at above 25 °C. These criteria are widely used in routine meteorological monitoring and early-warning systems (Kanti et al., 2022; Nairn et al., 2022; Perkins, 2015; Robinson, 2001). Some countries further adopt region-specific temperature thresholds based on local climatic characteristics to more accurately identify heatwave events (Guo et al., 2023; Xie and Zhou, 2023; Robinson, 2001). The specific criteria used by different organizations and countries to define heatwave events are summarized in Table 1.

In the literature we reviewed, only 75 papers provided a clear definition of heatwaves (Table S1). ~72% of these papers explicitly defined heatwave events, and ~43% of them employed historical statistical thresholds derived from long-term regional climate observations. The 90th percentile of maximum temperature was the most frequently employed relative threshold, adopted by ~12 papers. However, 26 literature applied absolute temperature thresholds, with >35 °C being the most commonly used criterion. Heatwave duration exhibited considerable variation across studies, with 2-5 days being the most frequently specified interval, although a few studies also considered single-day extreme heat events. The reported temperature thresholds ranged from 28 to 39 °C, reflecting substantial regional climatic diversity. This underscores the importance of accounting for local climatic conditions in defining extreme heat events (Shan et al., 2025; Wang et al., 2017; Yang et al., 2019). Overall, while existing studies share a broadly consistent conceptual framework for heatwave definition, the specific criteria, particularly temperature thresholds and duration, vary considerably across study region, spatial/temporal scales, and research objectives. Such heterogeneity hampers cross-regional comparability and reinforces the urgent need for a standardized, globally adaptable framework for heatwave identification (Conti et al., 2022; Xu et al., 2016).

4 Trends of heatwaves

4.1 Global heatwave occurrence and trends

In recent decades, global heatwaves have increased in frequency, intensity, spatial extent, and duration (Bekris et al., 2026; Perkins et al., 2012). Between 1950 and 2017, global heatwave days increased by 2.26 days per decade, while cumulative heat increased by 2.84 °C per decade (Perkins-Kirkpatrick and Lewis, 2020). Heatwave duration increases nonlinearly with climate warming, with this acceleration



intensifying under higher baseline temperatures (Han et al., 2022; Martinez-Villalobos et al., 2024; Perkins-Kirkpatrick and Gibson, 2017). Under the anthropogenic forcing, continental heatwaves have progressively shifted toward the equator, while the percentage of global land area affected by severe heatwaves has increased by approximately threefold since the early twentieth century (Barriopedro et al., 2023; Feng et al., 2025; Zhou et al., 2019). Pronounced increases in heatwave duration have been observed across Eurasia, North America, Africa, South America, and parts of West Asia (including the Middle East), along with widespread rises in cumulative heat intensity (Cai et al., 2024a; Wei et al., 2025). Marine heatwaves have also increased in frequency, intensity, and duration, while the Arctic has warmed at a rate far exceeding the global average, accompanied by substantial sea-ice loss and associated positive climate feedbacks (IPCC, 2023a; Oliver et al., 2018; Previdi et al., 2021; Yao et al., 2020). Heatwave characteristics also differ between arid and humid regions, with greater frequency observed in the former (Wang et al., 2024a). Heatwaves involve three key processes: horizontal advection of warm air, adiabatic warming in subsiding air, and diabatic heating near the surface, with their relative importance varying regionally (Mayer and Wirth, 2025). Atmospheric circulation, land-atmosphere interactions, and soil-moisture feedbacks also modulate heatwave development (Adeyeri et al., 2025; Mayer and Wirth, 2025; Miralles et al., 2019; Röthlisberger and Papritz, 2023). Overall, continued global warming is projected to substantially increase the frequency and intensity of heat extremes, with the magnitude of change increasing at each additional warming level. An extreme temperature event that occurred once every 10 years in the 1850-1900 climate is projected to occur about 4.1 times per decade at 1.5°C warming, 5.6 times per decade at 2°C, and 9.4 times per decade at 4°C, while its intensity is projected to increase by approximately 1.9°C, 2.6°C, and 5.1°C, respectively (IPCC, 2023a).

4.2 Heatwave occurrence and trends across regions

Heatwave trends across countries are broadly shaped by global warming, yet their frequency, duration, intensity, and seasonality exhibit marked regional contrasts, owing to difference in latitude, topography, atmospheric circulation, and human factors. China stands out as one of the regions most profoundly affected by shifting heatwave patterns, with substantial increases in frequency and severity since the 1990s (Bian et al., 2022; Li and Amatus, 2020; Lin et al., 2020; Liu and Li, 2025; Wu et al., 2023a). Heatwave occurrence in China exhibits pronounced spatial heterogeneity, with the Yangtze River



Basin (YRB), the Sichuan Basin, and southern China identified as major hotspots (Liu and Li, 2025). In northern China, heatwaves mainly occur in early summer, typically featuring larger diel temperature variability and higher peak intensity, whereas in southern China, they are concentrated in late summer (July-August), characterized by humid heat and a high frequency of tropical nights (Chen et al., 2023; Ding et al., 2024; Li et al., 2021; Wei et al., 2023; Zang et al., 2021). The frequency of compound heatwave events in China has steadily increased since the mid-1990s (Chen and Li, 2017; Su and Dong, 2019). These events encompass the co-occurrence of extreme heat with different environmental stressors, including drought, high humidity, air pollution, and nighttime heat, such compound events can produce amplified impacts on human compared with individual extremes (Chen, 2023; Hao et al., 2022; Su et al., 2025).

European heatwaves have undergone marked long-term intensification and seasonal expansion, with southern, central, and parts of northern Europe experiencing the most pronounced changes (Boboc et al., 2025; Lhotka and Kyselý, 2022; Rousi et al., 2022). From 2012 to 2020, western Europe experienced an increase in heatwave days at an estimated rate of 4.7 days per decade (Deng et al., 2022). Long-term observations have also indicated that 2011-2021 was one of the most active periods for heatwaves in Europe over the past century (Boboc et al., 2025). Heatwaves in Europe extend over a broad seasonal window, with increasing frequency observed from mid-to-late spring through early autumn (Boboc et al., 2025). European heatwaves are commonly associated with persistent high-pressure systems, subsidence, and warm-air advection, which can promote and sustain prolonged periods of extreme heat (Adeyeri et al., 2025; Feser et al., 2024). Moreover, the probability of such events is expected to rise further under projected warming (Ma et al., 2020; Russo et al., 2015).

Heatwave frequency in the United States has risen substantially since the mid-20th century, reaching about six events per year on average during the 2010s (Bhattarai et al., 2025). Historical heatwaves across the United States have become more frequent and intense, with particularly pronounced increases in the western and southwestern regions (Bhattarai et al., 2025; Oswald, 2018; Comeau et al., 2026). The characteristics of dry and humid heatwaves exhibit marked regional differences across North America (Yeo et al., 2026). Dry heatwaves in the southern United States are typically longer-lasting and more spatially extensive. However, humid heatwaves are more frequent in



210 northwestern North America and feature stronger warming and greater humid-heat stress than dry
 heatwaves (Yeo et al., 2026). Heatwaves in the United States also exhibit pronounced diel contrasts
 (Thomas et al., 2020). Inland cities generally exhibit greater heatwave intensity, whereas the South
 Coast experiences more persistent nighttime heatwaves (Bhattarai et al., 2025; Hulley et al., 2020).

In South America, the intensity and persistence of heatwaves increased substantially during 1979-2019,
 215 and heatwaves frequently occurred in conjunction with drought conditions (De Paula Corrêa, 2025;
 Marengo et al., 2026). In the tropical monsoon regions of Southeast Asia (e.g., Thailand, Vietnam, and
 Myanmar), heatwaves are influenced by long-term warming trends, large-scale circulation patterns,
 and climate modes such as El Niño (Thirumalai et al., 2017; Wang et al., 2026h; Lyu et al., 2024).
 Extreme heat substantially alters regional vegetation physiology and atmospheric VOC emissions (Bao
 220 et al., 2026; Janyasuthiwong et al., 2022). In India, heatwave frequency, total duration, and maximum
 event duration have all risen, driven primarily by climate modes including the El Niño-Southern
 Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (Lakshmi et al., 2026; Rohini et al., 2016).
 Although heatwave studies have been conducted in Africa, long-term, high-quality ground-based
 observations remain scarce, underscoring the need for further research across the region (Ceccherini
 225 et al., 2017; Chen and Wang, 2026; Kaspar et al., 2022). Overall, anthropogenic global warming
 primarily drives increases in heatwave frequency, duration, and intensity, while regional heatwave
 characteristics are shaped by large-scale circulation, air-sea interactions, land-atmosphere feedbacks,
 and urban heat-island effects (Barriopedro et al., 2023; Bi et al., 2026; IPCC, 2023a; Ramamurthy and
 Bou-Zeid, 2017).

230 **5 Heatwave-induced changes in ambient VOCs**

A literature review reveals that studies providing ambient VOCs data during heatwave events remain
 scarce. This study primarily involves six papers covering cities in China, South Korea, and the United
 Kingdom (UK), as shown in Table S2. Compared with non-heatwave periods, total VOCs (TVOCs)
 concentrations during heatwaves show a clear increasing trend (Churkina et al., 2017; Garg et al., 2026;
 235 Qin et al., 2025), with the dominant VOC groups being alkanes, alkenes and alkynes, aromatics, and
 oxygenated VOCs (OVOCs). For example, during the 2020 heatwave in Shanghai, China, the average
 concentrations of alkanes, alkenes and alkynes, aromatics, and OVOCs were 40.2, 14.2, 3.6, and



11.6 ppbv, respectively (Meng et al., 2023). There were substantial differences in the dominated VOC groups across different cities. For instance, in Chengdu, China, alkanes remained the dominant component during heatwaves, accounting for 68.1% and 72.5% of total VOCs in 2021 and 2022, respectively (Kong et al., 2025). However, in Xuzhou, China, the primary VOC group during heatwaves was OVOCs, contributing more than 50% of TVOCs (Zhang et al., 2024a). At most European sites, OVOCs also dominated TVOCs during heatwave events, reaching ~56% (Aas et al., 2026). Additionally, in Nantong, China, halocarbons accounted for a relatively high proportion of 28.9%, second only to alkanes at 31.9% (Chu et al., 2022).

The mixing ratios of dominated ambient VOC species during heatwave events from the six reviewed papers are shown in Fig. 1. During heatwaves, the average mixing ratios of acetone (4.14 ppbv), ethane (3.89 ppbv), propane (2.92 ppbv), and acetaldehyde (2.59 ppbv) were remarkably higher than those of any other species. The dominant VOC species exhibited substantial inter-city variability. For example, ethane and propane concentrations were substantial higher than any other species in Seoul, Chengdu, and Chongqing (Gil et al., 2026; Wang et al., 2024d). However, some cities were featured by OVOCs as the dominant VOC group. For instance, in Zaozhuang, China, acetone and acetaldehyde dominated during both dry and humid heatwaves, whereas in Essex, UK and in Nantong, China, acetone also showed the highest observed values (Lee et al., 2006; Wang et al., 2026a). Additionally, alkene also has considerable concentration under heatwaves. For example, ethylene concentrations in Chengdu, Seoul, and Zaozhuang were 1.66, 3.41, and 1.09 ppbv, respectively (Gil et al., 2026; Kong et al., 2025; Wang et al., 2026a). In European report, ethylene could account for ~15% of the total C2-C6 non-methane hydrocarbon mixing ratio (Aas et al., 2026).

In summary, during heatwaves, urban ambient VOCs concentrations commonly show a substantial increase, yet their chemical composition showed substantial inter-city variability. Alkanes dominate in some cities (e.g., Chengdu and Shanghai), while OVOCs prevail as the primary components in others (e.g., Xuzhou and European sites), and halocarbons also make notable contributions in particular locations (e.g., Nantong). This pronounced regional heterogeneity suggests that heatwaves affect urban VOCs composition in a complex, context-dependent manner. Future work should therefore integrate more observational data from a broader range of cities to better constrain the underlying mechanisms.



6 Effects of heatwaves on VOC emissions

6.1 Methods for investigating the effects of heatwaves on VOC emissions

Current methods for assessing heatwave impacts on VOC emissions encompass field observations and
270 controlled experiments (Aas et al., 2026; Huang et al., 2022; Tan et al., 2021), emission
parameterizations (Bourtsoukidis et al., 2024; Guenther et al., 1993; Wu et al., 2024), source
apportionment (Diao et al., 2025; Niu et al., 2021; Song et al., 2019), and observation-constrained
inverse modelling (Feng et al., 2024; Li et al., 2025a, 2026). These approaches provided
complementary insights and are often integrated and cross-validated to refine our understanding of
275 VOC emission responses, source variations, and their key drivers during heatwave events.

6.1.1 Field observations and controlled experiments

Field observations conducted at monitoring sites capture VOC variations under actual atmospheric
conditions, where source emissions, atmospheric transport, dispersion, and chemical processing jointly
influence observed VOC concentrations (Pfannerstill et al., 2024; Zeng et al., 2025). Field observation
280 methods involved analyzing the differences in VOC species concentrations and species composition
between heatwave periods and non-heatwave periods, to assess the impact of high temperatures on
VOC emission (Aas et al., 2026; Ferracci et al., 2020; Salvador et al., 2025). For instance, field
observations by Zhang et al. (2024a) showed that during a heatwave in Xuzhou, TVOC concentration
increased from 14.0 to 18.5 ppbv, with isoprene exhibiting the most pronounced response to high
285 temperatures, its peak concentration nearly doubled compared to that during non-heatwave periods.
Additionally, acetone, a typical anthropogenic OVOC tracer, also showed a clear temperature
dependence during the heatwave period. Pfannerstill et al. (2024) found that emissions of isoprene,
monoterpenes, sesquiterpenes, toluene, ethanol, and para-chlorobenzotrifluoride (PCBTF) increased
with rising temperature. Furthermore, other studies have used long-term continuous VOCs and
290 meteorological observations to analyze relationship between VOC species variations and temperature
(Debevec et al., 2021; Liu and Jaffe, 2026). According to long-term VOC measurements (2012-2014)
at the Ersa background station in Corsica, France, Debevec et al. (2021) found that three common
BVOCs, isoprene, α -pinene, and camphene, exhibited substantial seasonal and interannual variations,
which were closely related to changes in temperature and solar radiation, further indicating that



295 temperature and radiation conditions are important meteorological factors regulating ambient BVOC variability.

However, controlled experiments regulate environmental variables, e.g., temperature, radiation, and humidity, under controlled conditions to isolate temperature effects and elucidate the underlying mechanisms governing VOC emissions from specific sources or individual emission processes
300 (Nagalingam et al., 2023; Yáñez-Serrano et al., 2019). Depending on the emission source, temperature-response measurements are conducted using environmental chambers or branch- and whole-plant enclosure systems for vegetation (Birami et al., 2021; Lin et al., 2019), vehicle and fuel evaporation experiments for vehicular emissions (Huang et al., 2022; Rubin et al., 2006), and volatilization experiments involving solvents and VCPs (Tan et al., 2021).

305 **6.1.2 Emission parameterization**

The principle is to establish quantitative functions describing the relationships between VOC emission rates and key influencing factors such as temperature, solar radiation, vegetation conditions, and compound volatility, based on emission responses derived from observations or experiments (Guenther et al., 1993, 2012; Huang et al., 2022, 2015). These parameterizations are subsequently incorporated
310 into emission inventories and chemical transport models (CTMs) to estimate VOC emission variations under different meteorological conditions (Xu et al., 2025; Yan et al., 2021).

For BVOCs, empirical temperature response functions were initially developed to describe the responses of isoprene and monoterpene emissions to temperature and light, which ultimately led to the widely used BVOC emission parameterization schemes, exemplified by the G93 approach (Geron et al., 1994; Guenther et al., 1993, 1995). Isoprene emissions are commonly parameterized using light-
315 and temperature-dependent response functions (Table S3), with key inputs including the standard emission factor, photosynthetically active radiation, leaf temperature, light saturation parameters, and the temperature optimum. In contrast, monoterpene emissions were commonly modeled using an exponential temperature response function (Table S3), with key parameters including the standard
320 emission factor, current/reference temperature, and the β temperature response coefficient (Guenther et al., 1993). However, the temperature responses of BVOC emissions vary substantially among plant



species, ecosystem types, and compound classes, making a single temperature response coefficient insufficient to represent emission variability under complex environmental conditions (Bourtsoukidis et al., 2024; Komenda and Koppmann, 2002; Li et al., 2025c; Zeng et al., 2025). Advances in
325 understanding of BVOC emission mechanisms have driven a gradual shift in parameterization schemes, from simple empirical temperature functions toward more process-based approaches. Process-oriented models like the Model of Emissions of Gases and Aerosols from Nature (MEGAN) incorporate temperature and other controlling factors (i.e., radiation, leaf area index, plant functional types, and plant physiological status), thereby providing a mechanistic description of BVOC emissions. In these
330 models, temperature response factors are partitioned into light-dependent and light-independent components. The former accounts for the enzymatic temperature response of de novo synthesized BVOCs (e.g., isoprene), while the latter applies exponential functions to represent the temperature dependence of stored or volatility-driven compounds (e.g., monoterpenes) (Guenther et al., 2006, 2012; Sindelarova et al., 2014; Wang et al., 2024c). Current temperature correction factors are mainly derived
335 from a limited number of plant species and ecosystems. Consequently, uncertainties remain regarding species-specific responses, shifts in plant functional types, and vegetation structure changes under future climate scenarios.

For AVOCs, temperature-dependent parameterizations have been primarily applied to several temperature-sensitive source categories, including vehicular evaporative emissions, fuel storage,
340 solvent use, coating applications, and VCP emissions (Table S3). Vehicular evaporative VOC emissions are one of the best-constrained temperature-sensitive processes among anthropogenic sources. Vehicle emission measurements and inventory methodologies have demonstrated that ambient temperature, fuel vapor pressure, fuel composition, and vehicle emission standards strongly influence evaporative emission factors and their temperature dependence (EEA, 2019; Huang et al., 2022; Lu et al., 2025; Wu et al., 2024). Fuel storage VOC emissions are also strongly associated with ambient
345 temperature, fuel vapor pressure, and storage tank characteristics. Therefore, emission estimation approaches typically incorporate tank configuration, fuel properties, meteorological conditions, and operational parameters into inventory frameworks (US EPA, 2024; Wang et al., 2021b; Yang et al., 2024). For solvent use, coating applications, and other VCP emissions, increasing temperature
350 promotes VOC release by elevating organic vapor pressures, enhancing internal diffusion, and



accelerating surface volatilization (Huang et al., 2015; Mo et al., 2021; Wu et al., 2024; Xu et al., 2025). Overall, existing AVOC temperature-dependent parameterizations, largely derived from typical meteorological conditions or limited experimental datasets, resulting in substantial uncertainties in representing the temperature sensitivity of emerging anthropogenic sources, particularly VCP emissions, under extreme heatwave conditions.

6.1.3 Source apportionment

The approach typically used observed VOC species concentrations as inputs for source apportionment models to quantify source contributions, while also incorporating meteorological variables such as temperature, solar radiation, and boundary layer height, to investigate variations in VOC source contributions under heatwave conditions (Diao et al., 2025; Song et al., 2019). Among current source apportionment methods, Positive Matrix Factorization (PMF) is one of the most widely applied methods for VOC source identification (Yang et al., 2022). PMF decomposes the observed or initial VOC (i.e., ambient concentrations that would have been present at the monitoring site had they not undergone chemical processing in transit from the sources) concentration matrix into source profile and contribution matrix, therefore identifying major emission categories based on tracer species (Hopke, 2016; Paatero and Tapper, 1994). This apportioned results provide a basis for assessing the responses of different emission sources to elevated temperatures (Liu et al., 2023; Song et al., 2019).

PMF-based studies generally establish the relationship between heatwaves and VOC source variations through two methods. The first approach relates PMF-resolved source contributions to temperature and other meteorological variables through temperature-stratified (Song et al., 2019) or multivariate analyses (Chen et al., 2024c), thereby characterizing source-specific associations with temperature. The second method splits observation periods into heatwave and non-heatwave episodes, directly compares differences in source contributions between the two periods, thereby identifying emission sources with the strongest enhancements and their relative importance during heatwave episodes (Kong et al., 2025; Niu et al., 2021; Qu et al., 2025). Additionally, ambient VOCs can undergo substantial photochemical losses during transport from the emission sources to the observation sites (Gu et al., 2025; Yang et al., 2022; Yuan et al., 2012). Under heatwave conditions, enhanced solar radiation and atmospheric oxidative capacity can accelerate the photochemical losses of reactive VOCs



380 (Kong et al., 2025; Liu et al., 2023). Therefore, source apportionment based on the observed data could underestimate the contributions of highly temperature-sensitive emission sources (Gu et al., 2023; Liu et al., 2023, 2024; Wu et al., 2023b). To address this issue, a photochemical age-based parameterization method has been applied to estimate the initial concentrations of ambient VOCs and correct for photochemical losses, with the corrected data then incorporated into PMF source apportionment
385 (termed IC-PMF). However, given that the chemical losses of VOCs during transport from emission sources to receptor sites are actually the true contributors to concurrent O₃ or SOA formation, Gu et al. (2023) and Cui et al. (2024) developed a consumed-VOC source apportionment approach (i.e., C-PMF). Diao et al. (2025) further used the C-PMF results, combined with atmospheric temperature data, to systematically analyze the effects of high temperatures on the consumption of VOCs emitted
390 from different sources. Nevertheless, relevant studies remain fewer.

Overall, source apportionment is an effective tool for identifying VOC sources and quantifying their temperature sensitivities during heatwave events. However, their reliability remains dependent on quality of measurement data and underlying statistical assumptions, and their ability to resolve complex regional transports and atmospheric chemical transformations remains limited.

395

6.1.4 Observation-constrained inverse modeling

Inverse modeling has emerged as an important approach for quantitatively assessing VOC emissions and their responses to environmental changes. Unlike emission parameterization approaches, which rely on predefined emission factors and temperature response functions (Guenther et al., 1993; Xu et al., 2025), inverse modeling starts from atmospheric observations and uses CTMs to establish the
400 relationship between source emissions and ambient receptor concentrations (Li et al., 2025a; Oomen et al., 2024; Xu et al., 2026). Inverse methods minimize the mismatch between modeled and observed concentrations, thereby updating prior emission inventories to yield posterior estimates that more closely reflect ambient conditions (Stavrakou et al., 2009, 2015).

405 Among current reports, isoprene represents the most extensively investigated compound (Bauwens et al., 2016; Kaiser et al., 2018). Early studies primarily used satellite-derived HCHO column observations from instruments (e.g., the Global Ozone Monitoring Experiment (GOME) and the Ozone



Monitoring Instrument (OMI) to constrain regional and global emissions of isoprene and other BVOCs, as well as some non-methane volatile organic compounds (NMVOCs) (Millet et al., 2008; Palmer et al., 2006). These satellite-based constraints have been widely applied to evaluate and/or improve process-based emission models (e.g., MEGAN) and bottom-up emission inventories (Bauwens et al., 2016; Kaiser et al., 2018). With the development of next-generation satellite observations, including the Tropospheric Monitoring Instrument (TROPOMI) and the Cross-track Infrared Sounder (CrIS), inverse modeling methods have expanded from HCHO-based indirect constraints to multi-species constraints using HCHO-CHOCHO combinations and direct retrievals of isoprene columns, improving the capability to resolve the spatial and temporal variability of different VOC sources (Oomen et al., 2024; Sfindla et al., 2026; Xu et al., 2026). Furthermore, inverse modeling could identify the impacts of temperature variability on VOC emissions by examining interannual anomalies and extreme climate events (Li et al., 2026; Stavrakou et al., 2018). For example, Li et al. (2025a) used CrIS-derived isoprene column observations to infer enhanced emissions during the 2015-2016 El Niño event and the 2019-2020 extreme heat event.

Overall, current VOC inverse modeling methods largely rely on satellite-derived secondary products, such as HCHO and CHOCHO, which provide strong constraints on reactive VOCs (e.g., isoprene) but remain limited for less reactive VOCs and complex anthropogenic sources. Moreover, satellite-derived emission estimations were subject to uncertainties from atmospheric chemical processes and retrieval limitations. Despite these challenges, observation-constrained inversion offers unique advantages for investigating large-scale VOC emission variability.

6.2 Effects of heatwaves on AVOC sources

Heatwaves are a major meteorological driver of AVOC emissions (Qin et al., 2025; Xian et al., 2026). Unlike emissions, which are primarily controlled by activity levels and energy consumption, elevated temperatures directly alter the volatilization and mass transfer of organic compounds, thereby enhancing the release of various temperature-sensitive AVOCs (Qu et al., 2025; Wu et al., 2024). In recent years, increasing frequency and intensity of global heatwave events have drawn growing attention to heatwave-driven changes in AVOC emissions (Diao et al., 2025; Huang et al., 2015; Zhu et al., 2024) (Table S4). Current studies suggests that AVOC concentrations, emission fluxes, or source



contributions can increase to varying degrees during heatwave events (Kong et al., 2025; Song et al., 2019). However, the magnitude of these changes is highly variable and depends on regional emission source profiles, pollution control levels, and heatwave intensity (Aas et al., 2026; Dufresne et al., 2025; 440 Qin et al., 2025).

Solvent use, VCPs, fuel storage and handling, and vehicular evaporative emissions are among the most well-established temperature-sensitive AVOC sources (Huang et al., 2015; Lu et al., 2025; Tan et al., 2021; Yang et al., 2024; Yue et al., 2020). Solvent use and VCPs represent the typical volatilization-driven anthropogenic VOC sources, and their temperature dependence is governed by the volatility of 445 organic constituents, product usage patterns, vapor pressure, and gas-liquid/gas-solid mass transfer processes (McDonald et al., 2018; Seltzer et al., 2021). Given that VCPs are typically emitted in open or semi-open environments during application and curing, elevated ambient temperatures directly accelerate VOC volatilization and diffusion (Gkatzelis et al., 2021; Pfannerstill et al., 2024; Zhu et al., 2024). Wu et al. (2024) found that solvent-used AVOC emissions in the Beijing-Tianjin-Hebei (BTH) 450 region exhibit a strong temperature dependence, with a sensitivity of approximately $5.8\% \text{ K}^{-1}$. Qin et al. (2025) further integrated laboratory experiments with modeling analyses and found that an increase in total VOC emissions by a factor of ~ 2 from solvent-based paint at 40°C relative to that at 25°C . A recent heatwave study in the Sichuan Basin further reported that solvent-related AVOC emissions increased by $\sim 21.9\%$ under heatwave conditions, corresponding to an average temperature rise of $\sim 3^\circ\text{C}$ 455 (Xian et al., 2026). In addition, emission experiments on building materials and coatings have shown that VOC release rates rise with temperature (Huang et al., 2015; Tan et al., 2021; Xiong et al., 2013).

Both fuel storage/handling processes and vehicular evaporative sources show pronounced temperature dependence (Rubin et al., 2006; Wang et al., 2021b; Yang et al., 2024; Zhang et al., 2024b). Vehicular evaporative fuel emissions are primarily governed by fuel volatility and composition, fuel and ambient 460 temperatures, fuel-tank headspace volume, and the performance of evaporative emission-control systems (Huang et al., 2022; Yue et al., 2020; Zhang et al., 2024b). Increasing temperatures raise the vapor pressure of volatile fuel components and promote their partitioning into the fuel-tank headspace, thereby increasing vapor generation and potentially enhancing diurnal, hot-soak, and running-loss emissions (Lu et al., 2025; Rubin et al., 2006; Yan et al., 2021; Yang et al., 2024). Huang et al. (2022)



465 conducted variable-temperature sealed-chamber experiments and reported a strong temperature
dependence of vehicle evaporative hydrocarbon emissions, with values at 313K being 12.3-26.7 times
those at 298K. Wu et al. (2024) further quantified the temperature sensitivity of vehicular emissions,
showing that traffic-related AVOC emissions in the BTH region increased by up to 9.7% K⁻¹ with rising
temperature. In the Sichuan Basin, traffic-related evaporative AVOC emissions were approximately
470 26.7% higher during heatwave than under non-heatwave conditions (Xian et al., 2026). National-scale
road traffic emission inventories for China further indicated that higher summer temperatures
substantially boost vehicular evaporative emissions, resulting in actual emissions that exceed
uncorrected baseline estimates (Yan et al., 2021). For fuel storage emissions, data from floating-roof
tank observations suggested that elevated storage temperatures remarkably enhance standing and rim-
475 seal losses, implying that fuel storage and handling operations contribute substantially to AVOC
emissions under heatwave conditions (US EPA, 2024; Wang et al., 2021b; Yang et al., 2024).

However, combustion-related sources (e.g., vehicle exhaust and industrial combustion,) generally
exhibit lower direct temperature sensitivity than volatilization-driven sources (Diao et al., 2025;
Pfannerstill et al., 2024; Wu et al., 2024). These emissions are primarily governed by fuel consumption,
480 combustion conditions, emission standards, and activity levels, but are largely independent of ambient
temperature (Qu et al., 2025; Xu et al., 2025; Yan et al., 2021). Nevertheless, extreme heatwaves might
indirectly affect certain combustion-related emissions through increased cooling demand, higher
electricity loads, changes in transport activity, and industrial operational adjustments (Chen et al.,
2024b; Li et al., 2024).

485

6.3 Effects of heatwaves on BVOC sources

Temperature is a key environmental driver of BVOC emissions (Bourtsoukidis et al., 2025; Chen et
al., 2026; Yang et al., 2026a). These emissions are directly governed by plant physiological processes,
including photosynthetic metabolism, enzyme activity, leaf temperature, stomatal behavior, and stress
490 responses, and thus respond more rapidly and sensitively to temperature changes than to other
environmental factors (Guenther et al., 2006; Peñuelas and Staudt, 2010). At global and regional scales,
isoprene, monoterpenes, sesquiterpenes, and selected OVOCs consistently show strong temperature



dependence (Table S5). This relationship is embedded in widely used BVOC emission models (e.g., MEGAN) and serves as a key parameterization basis for interpreting seasonal, spatial, and interannual variability of BVOC emissions (Chen et al., 2026; Guenther et al., 2012; Seco et al., 2022; Sindelarova et al., 2014; Wang et al., 2024b, c).

Isoprene is among the most temperature-sensitive and extensively studied BVOCs (Debevec et al., 2021; Guenther et al., 1993, 2012; Seco et al., 2022). It is synthesized *de novo* in leaves and rapidly emitted, with emissions closely tied to leaf temperature, light availability, and enzymatic activity (Li et al., 2011; Yáñez-Serrano et al., 2019). Numerous studies show that isoprene emissions rise rapidly with leaf temperature and photosynthetically active radiation (PAR) within the optimal physiological temperature range (Angot et al., 2020; Lin et al., 2019). For instance, Seco et al. (2022) found that experimental warming by 2 °C and 4 °C increased isoprene emissions from Arctic tundra vegetation by approximately 41% and 87%, respectively. Recent satellite-based inversion studies further show that isoprene emissions in the YRB and Sichuan-Chongqing regions increased by more than 130% in 2022 under elevated temperature conditions relative to the 2020-2021 average, with enhancements exceeding 150% during extreme heat events (Wang et al., 2026d). However, isoprene emissions do not increase indefinitely with temperature but instead show strong nonlinearity (Li et al., 2011; Wang et al., 2024b). When temperatures reach or exceed plant physiological tolerance limits, suppressed photosynthesis, altered enzymatic activity, and thermal damage can cause emissions to plateau or decline (Wang et al., 2024b; Yang et al., 2026a; Zeng et al., 2025). Heatwaves and compound heatwave-drought stress add further uncertainty to isoprene emission responses (Chen et al., 2026; Li et al., 2025c). Short-term warming may stimulate isoprene synthesis and release, and isoprene emissions may even increase as photosynthetic carbon assimilation declines (Bamberger et al., 2017; Yáñez-Serrano et al., 2019). However, prolonged heat stress or water limitation reduces carbon availability and metabolic capacity, thereby constraining further emission increases (Ferracci et al., 2020; Li et al., 2025c).

The temperature response of monoterpene emissions can be divided into two categories. For plant species containing specialized storage structures, such as resin ducts, oil glands, or glandular trichomes, elevated temperatures accelerate volatilization and diffusion, thereby facilitating the rapid release of



stored terpenoids (Birami et al., 2021; Nagalingam et al., 2024; Zeng et al., 2026a). Consequently, emissions of stored monoterpenes typically exhibit an exponential increase with temperature (Bourtsoukidis et al., 2024; Lindwall et al., 2016; Nagalingam et al., 2023). For instance, Komenda and Koppmann (2002) observed strong temperature dependence for individual monoterpene emissions
525 in field measurements of Scots pine, with β temperature coefficients ranging from 0.08 to 0.13 K⁻¹. Bourtsoukidis et al. (2024) later reported a widespread temperature sensitivity across multiple species, with a mean β of ~0.13 K⁻¹, though substantial variability persisted among plant functional types, species, and individual compounds. For monoterpenes that rely in part on de novo synthesis pathways, their temperature responses are further governed by photosynthesis, enzyme regulation, and carbon
530 substrate supply (Staudt et al., 2017). Moderate warming may enhance monoterpene biosynthesis and release; however, under severe heatwaves, reduced photosynthetic capacity and limited substrate availability can weaken de novo synthesis and counteract the enhanced volatilization from storage pools, thereby diminishing or even reversing emission increases (Kleist et al., 2012; Li et al., 2025c).

Sesquiterpenes exhibit temperature responses broadly comparable to those of monoterpenes and are
535 routinely parameterized using β temperature response coefficients (Birami et al., 2021; Lindwall et al., 2016). However, sesquiterpenes have lower volatility yet higher chemical reactivity than monoterpenes, which promotes rapid atmospheric oxidation and reduces ambient concentrations, thereby making their observation and quantification more challenging (Bourtsoukidis et al., 2025). Moreover, sesquiterpene emissions are strongly modulated by species-specific traits, storage tissues,
540 and physiological processes, leading to considerable variability in reported temperature response parameters across studies (Bourtsoukidis et al., 2012; Staudt et al., 2017).

In addition to isoprene, monoterpenes, and sesquiterpenes, biogenic OVOCs constitute another important compound class that warrants attention under heatwave events (Contreras-Serrano et al., 2025; Werner et al., 2020). Methanol, acetone, acetaldehyde, and other oxygenated compounds arise
545 from plant growth, cell wall metabolism, leaf damage, and stress-induced responses (Birami et al., 2021; Seco et al., 2007). Their emissions are governed not only by temperature but also by phenological stage, tissue damage, water availability, and oxidative processes (Schade et al., 2011). For instance, Cai et al. (2021) found that methanol emissions from spring wheat generally increased



with temperature over 3-35 °C, while excessive temperatures could either suppress emissions via
550 enzyme inactivation or induce transient bursts from heat injury. Likewise, Hakola et al. (2017)
observed that acetone and C₄-C₁₀ aldehyde emissions from Norway spruce were low in spring, rose
progressively through summer, and peaked in July, suggesting a joint regulation by seasonal
temperature changes and plant physiological status. Therefore, biogenic OVOCs are expected to show
enhanced emissions and altered compositions under heatwave; however, their responses remain highly
555 complex and urgently require further quantification through systematic field observations and
controlled experiments.

7 Effects of heatwaves on VOC transformation mechanisms

7.1 Studying methods for transformation mechanisms

560 Heatwave impacts on VOC transformation are governed by multiple coupled processes, including
precursor availability (Pfannerstill et al., 2024; Wang et al., 2026e), gas-phase oxidation (Aas et al.,
2026; Wang et al., 2022, 2026d), radical cycling (Yang et al., 2025; Zhang et al., 2024a), O₃ formation
sensitivity (Liu et al., 2026a; Wang et al., 2026g; Zhou et al., 2026), low-volatility product formation
(Deng et al., 2021; Shahin et al., 2025), gas-particle partitioning (Serrano Damha et al., 2024; Shiraiwa
565 and Pöschl, 2021), and multiphase reactions (DeRieux et al., 2018; Zeng et al., 2026b). Meanwhile,
heatwave events often coincide with enhanced solar radiation, reduced humidity, altered boundary
layer structure, and stagnant meteorology, such that the direct temperature effects on chemistry become
intertwined with concurrent changes in emissions, photolysis, and atmospheric transport (Schnell and
Prather, 2017; Zhao et al., 2019; Zhou et al., 2025). Therefore, the key objective of related studies is
570 not merely to compare O₃ or SOA concentrations under high-temperature versus normal conditions,
but rather to identify the temperature-sensitive processes in VOC transformation pathways and to
quantitatively partition the relative contributions of precursor availability, chemical reactions, and
physical transport. Current studies commonly rely on field observations (Fu et al., 2024; Pfannerstill
et al., 2024), smog chamber and reactor experiments (Baker et al., 2024; Deng et al., 2021), box and
575 process-based models (Kong et al., 2025; Shiraiwa and Pöschl, 2021), as well as CTMs (Churkina et
al., 2017; Porter and Heald, 2019; Wang et al., 2026f), to examine heatwave impacts on VOC
transformation mechanisms.



7.1.1 Field observations

580 Field observations are a fundamental tool for identifying VOC transformation changes during actual heatwave events (Cai et al., 2024b; Pfannerstill et al., 2024). Typically, studies distinguish heatwave from non-heatwave periods using temperature thresholds and duration criteria, and then compare precursor concentrations and composition, oxidation levels, and secondary pollutant formation between the two periods (Fu et al., 2024; Lee et al., 2006).

585 To investigate VOC-to-O₃ transformation, gas chromatography-mass spectrometry (GC-MS) and proton-transfer-reaction time-of-flight mass spectrometry (PTR-ToF-MS) are commonly employed to characterize variations in VOC concentrations and compositions between heatwave and non-heatwave periods (Aas et al., 2026; Churkina et al., 2017; Zhang et al., 2024a). These measurements are further combined with indicators such as OH reactivity (OHR) and ozone formation potential (OFP) to assess
590 changes in highly reactive VOC species and precursor availability under elevated temperatures (Pfannerstill et al., 2024; Pusede et al., 2014). Additionally, simultaneous measurements of HONO, carbonyls, O₃, photolysis frequencies, and other photochemical parameters can provide additionally constraints on changes in atmospheric oxidative capacity and O₃ formation conditions during heatwaves (Wang et al., 2026b; Zhou et al., 2025). According to the VOC and NO_x measurements,
595 together with direct O₃ production rate observations or observation-based statistical diagnostics, field studies can further evaluate whether O₃ formation regimes transition from VOC-limited to transitional or NO_x-limited conditions during heatwaves (Liu et al., 2026a; Pusede and Cohen, 2012; Zhou et al., 2026). Moreover, the nonlinear O₃-temperature relationship can be exploited to identify turning points in O₃ responses to extreme heat, encompassing reduced sensitivity, saturation, or even O₃ formation
600 decline at very high temperatures (Fu et al., 2024; Wang et al., 2026b).

For VOC-to-SOA transformation, field observations typically involve measurements of gas-phase VOCs, semi-volatile and intermediate-volatility organic compounds (S/IVOCs), OVOCs, and particle-phase organic components. These data are then used to compare changes in precursor composition, oxidation state, volatility, and organic aerosol composition between heatwave and non-heatwave
605 periods (Cai et al., 2024b; Nie et al., 2022; Zhang et al., 2024c). Combined with analytical techniques



including aerosol mass spectrometry, chemical ionization mass spectrometry, and thermal desorption methods, these observations can characterize variations in SOA formation potential (SOAFP), oxidative processing of organic aerosol, and gas-particle partitioning under elevated-temperature conditions, thereby evaluating the impacts of heatwaves on SOA formation (Hass-Mitchell et al., 2024; Zeng et al., 2026b).

Field observations can directly capture heatwave-induced changes in VOCs and their secondary products. However, heatwave temperatures often covary with enhanced radiation, boundary layer evolution, reduced humidity, and regional transport, complicating the isolation of purely temperature-driven chemical effects from concentration data alone. Moreover, previous studies have mainly focused on individual heatwave events or a limited number of urban regions (Aas et al., 2026; Wang et al., 2026b; Zhang et al., 2024a,c), while long-term continuous observations and coordinated measurements of key species, including radicals, S/IVOCs, and gas- and particle-phase oxygenated organic compounds, remain insufficient.

7.1.2 Smog chamber and reactor experiments

Smog chamber, oxidation flow reactor, and environmental chamber experiments serve as key approaches to isolate the direct effects of temperature and to derive mechanistic parameters (Carter et al., 2002; Deng et al., 2021; Schmedding et al., 2020; Shahin et al., 2025). These experiments typically regulate temperature, relative humidity, oxidant levels, and other environmental variables independently to examine the temperature dependence of VOC oxidation rates, product distributions, radical reaction pathways, SOA yields, gas-particle partitioning, and particle-phase reactions (Baker et al., 2024; Yang et al., 2025).

For VOC-to-O₃ transformation, smog chamber and environmental chamber experiments are primarily used to determine O₃ formation reactivity of different VOC species, investigate VOC-NO_x photochemical processes, and evaluate gas-phase chemical mechanisms (Carter, 2010; Carter et al., 1995; Morino et al., 2023). A limited number of temperature-controlled studies have compared VOC consumption, NO-to-NO₂ conversion, and O₃ formation processes at different temperatures, showing



that increasing temperature can increase O₃ production rates in certain hydrocarbon-NO_x systems (Carter et al., 2002). However, experiments specifically designed to investigate temperature effects on O₃ formation remain limited. Changes in O₃ production efficiency and VOC-NO_x chemical regimes under realistic heatwave conditions require further investigation by integrating chamber experiments with field observations and modeling approaches.

For SOA studies, temperature-controlled experiments enable separate assessment of temperature effects on VOC oxidation, low-volatility product formation, gas-particle partitioning, and multiphase processes (Deng et al., 2021; Lannuque et al., 2023; Shahin et al., 2025). By measuring VOC consumption, oxidation product composition, formation of highly oxygenated organic molecules (HOMs), and SOA yield variations across different temperatures, these experiments can elucidate the temperature-modulated shifts in VOC oxidation pathways and the production of low-volatility species (Deng et al., 2021; Ehn et al., 2014; Zhang et al., 2024c). Meanwhile, simultaneous measurements of gas-phase and particle-phase organic compounds allow characterization of temperature-induced changes in product volatility, oxidation state, and gas-particle partitioning behavior (Deng et al., 2021; Lannuque et al., 2023; Odum et al., 1996; Shahin et al., 2025). By controlling temperature, relative humidity, particle liquid water content, and other environmental parameters, these experiments can further investigate changes in particle-phase state and their impacts on oxidation product uptake and mass transfer processes under heatwave conditions (DeRieux et al., 2018; Gaston et al., 2014; Li and Knopf, 2021; Zhang et al., 2018). While these controlled experiments provide direct insights into temperature-dependent chemical processes, most laboratory studies rely on simplified precursor systems and aerosol conditions, which limits their representativeness of the full complexity of ambient heatwave environments.

655

7.1.3 Box models and process-based models

Box models and process-based models are key tools for elucidating the processes governing VOC chemical transformation and SOA formation under heatwave conditions at the local scale (Kong et al., 2025; Meng et al., 2023; Shiraiwa and Pöschl, 2021). Box models are typically constrained by observational data to simulate gas-phase chemical mechanisms using and to calculate net O₃ production rates (Ma et al., 2022; Zhang et al., 2024a). Process-based models primarily describe gas-

660



particle partitioning, interfacial mass transfer, reactive uptake, and diffusion and reactions within particles, thereby investigating the controlling processes of SOA formation and preservation (Schervish and Shiraiwa, 2023; Zhu et al., 2025).

665 For O₃ studies, box models typically use observations of VOCs, HONO, O₃, photolysis frequencies, and meteorological parameters during heatwave and non-heatwave periods as input constraints (Coates et al., 2016; Wang et al., 2022; Zhang et al., 2024a). When coupled with detailed chemical mechanisms such as the Master Chemical Mechanism (MCM) and Regional Atmospheric Chemistry Mechanism (RACM), these models simulate the formation, transformation, and loss processes of OH, HO₂, and
670 RO₂ radicals, quantify the reactivity of individual VOCs, identify key reaction fluxes, and calculate net O₃ production rates, thereby elucidating the influence of heatwaves on O₃ formation (Kong et al., 2025; Meng et al., 2023; Wang et al., 2022; Ye et al., 2023). Further integration with VOC and NO_x reduction scenarios, relative incremental reactivity (RIR), or ozone isopleth analysis enables diagnosis of whether O₃ formation occurs under VOC-limited, transitional, or NO_x-limited regimes and how
675 these regimes shift during heatwave events (Coates et al., 2016; Li et al., 2024; Wang et al., 2019). However, uncertainties in temperature-dependent and photochemically sensitive processes, such as PAN thermal decomposition, HONO production, and RO₂ chemistry, still limit quantitative attribution of heatwave impacts on O₃ formation.

For SOA studies, box models generally use observations of VOCs, NO_x, oxidants, temperature,
680 humidity, and photolysis frequencies during heatwave and non-heatwave periods as inputs, combined with detailed gas-phase chemical mechanisms to simulate multigenerational VOC oxidation, HOM formation, and the production of low-volatility oxidation products (Aas et al., 2026; Schervish and Shiraiwa, 2023). These approaches allow assessment of the impacts of elevated temperature on VOC oxidation pathways and product formation (Shen et al., 2024; Zhu et al., 2025). Based on these
685 simulations, the Volatility Basis Set (VBS) framework and absorptive partitioning models further describe the evolution of product volatility and temperature-driven changes in gas-particle partitioning, including temperature-induced evaporation of semi-volatile organic compounds and the redistribution of oxidation products toward lower-volatility species during atmospheric aging (Odum et al., 1996; Pankow, 1994; Serrano Damha et al., 2024). For particle-phase processes, process-based models,



690 including resistance models and the KM-GAP kinetic multilayer model, simulate particle-phase mass transfer and multiphase chemical processes to evaluate how changes in particle viscosity and molecular diffusion under heatwave conditions influence oxidation product uptake, particle-phase transformation, and SOA preservation (Li and Knopf, 2021; Schervish and Shiraiwa, 2023; Shiraiwa and Pöschl, 2021). However, uncertainties remain in the representation of S/IVOC oxidation, multigenerational chemistry, 695 HOM formation, and temperature-dependent gas-particle partitioning.

7.1.4 Chemical transport models

The CTMs are essential tools for quantitatively assessing the combined effects of emission changes, chemical transformation, and physical transport during heatwave events (Pan et al., 2026; Wang et al., 700 2021a, 2026b,g). Models such as the Weather Research and Forecasting coupled with Community Multiscale Air Quality (WRF-CMAQ), the Weather Research and Forecasting coupled with Chemistry (WRF-Chem), and the Goddard Earth Observing System Chemical transport model (GEOS-Chem) are capable of simulating VOC and NO_x emissions, gas-phase photochemistry, SOA formation, boundary layer mixing, regional transport, and deposition at both regional and global scales (Porter and Heald, 705 2019; Pu et al., 2017; Wang et al., 2021a). By designing baseline and sensitivity simulations, in which temperature-sensitive emissions, heatwave meteorological conditions, and chemical process parameters are selectively modified, CTMs can quantitatively separate the relative contributions of emission changes, chemical transformation, and physical transport to variations in O₃ and SOA during heatwave events (Qin et al., 2025; Wang et al., 2026d, 2025).

710 For O₃ studies, CTMs can quantify the contributions of temperature-driven increases in precursor emissions, active nitrogen recycling, and enhanced radical chemistry by independently modifying temperature-sensitive VOC emissions, soil NO emissions, PAN thermal decomposition processes, and reaction rate parameters (Porter and Heald, 2019; Qin et al., 2025; Wang et al., 2026b, d, f). Meanwhile, O₃ process analysis and sensitivity simulations can further distinguish the contributions of local 715 photochemical production, regional transport, and boundary layer changes to heatwave-associated O₃ enhancement (Pan et al., 2026; Wang et al., 2021a; Zhou et al., 2025). In addition, by perturbing VOC and NO_x emissions or applying Empirical Kinetic Modeling Approach (EKMA) curves and HCHO/NO₂ indicators, the models can evaluate shifts in O₃ production efficiency and VOC-NO_x



sensitivity regimes under heatwave conditions, thereby determining whether O₃ formation regimes
720 shift from VOC-limited toward transitional or NO_x-limited states (Sun et al., 2026; Wang et al., 2026g,
2025). However, uncertainties in temperature-sensitive emission parameterizations and simplified
representations of key chemical processes, including PAN decomposition and RO₂ chemistry, still
hinder the robust attribution of heatwave-driven O₃ increases.

For SOA studies, CTMs can employ multiple sensitivity simulations to systematically separate the
725 pathways through which heatwaves influence SOA formation (Horne and Dabdub, 2017; Wang et al.,
2026e). Modifications of meteorological fields and oxidation reaction rates can quantify direct effects
associated with enhanced photochemical oxidation and shifts in gas-particle partitioning caused by
increasing temperature (Dawson et al., 2007; Wang et al., 2026d; Yin et al., 2026). Meanwhile, the
incorporation of temperature-dependent VOC emissions allows assessment of the contribution of
730 increased precursor availability to SOA formation during heatwaves (Churkina et al., 2017; Wang et
al., 2026d). Furthermore, some models have incorporated parameterizations of SOA phase state and
viscosity to evaluate how temperature changes affect particle-phase diffusion limitations, reactive
uptake, and continued SOA evolution (Schmedding et al., 2020; Yin et al., 2026). Similar to O₃ studies,
uncertainties in temperature-dependent SOA precursor emissions and simplified representations of
735 oxidation and multiphase processes remain major challenges.

7.2 Mechanisms and controlling factors of VOC-to-O₃ transformation under heatwave

The fundamental mechanism of VOC-driven O₃ formation involves the coupling of VOC oxidation
with NO_x photochemical cycling (Atkinson, 2000; Coates et al., 2016). Near-surface O₃ is not directly
emitted but is formed photochemically via radical chain reactions involving reduced gases, such as
740 VOCs, CO, and CH₄ together with NO_x under solar radiation (Coates et al., 2016; Elshorbany et al.,
2024; Finlayson-Pitts and Pitts, 1997). Therefore, the critical role of VOCs in O₃ formation lies not in
direct O₃ production, but rather in the generation of organic peroxy radicals and oxidation
intermediates that promote the conversion of NO to NO₂, thereby sustaining O₃ accumulation
(Atkinson and Arey, 2003; Monks et al., 2015; Sillman, 1999). A growing body of studies further
745 indicates that heatwaves can profoundly influence O₃ formation by modulating precursor availability,
atmospheric oxidative capacity, and O₃ formation regimes (Qin et al., 2025; Sun et al., 2026; Wang et



al., 2023, 2026g).

First, heatwaves can enhance emissions from temperature-sensitive VOC sources, altering the abundance, chemical composition, and overall reactivity of VOC precursors involved in O₃ formation (Diao et al., 2025; Li et al., 2025c; Qin et al., 2025). BVOCs, particularly isoprene and monoterpenes, exhibit strong temperature dependence, while anthropogenic evaporative sources, including vehicle evaporation and VCPs, may also increase under heatwave conditions (Huang et al., 2022; Qin et al., 2025; Salvador et al., 2025). However, the degree to which heatwaves promote O₃ formation depends not merely on the magnitude of VOC emission increases, but also on the chemical reactivity of the emitted species (Atkinson, 2000; Carter, 2010; Pusede et al., 2014). Recent studies further indicate that increases in highly reactive VOC species, such as isoprene, alkenes, and aromatics, can exert stronger impacts on O₃ production than increases in less reactive alkanes during heatwave periods (Kong et al., 2025; Pfannerstill et al., 2024).

Second, heatwaves are generally accompanied by clear-sky conditions, enhanced solar radiation, and elevated photolysis frequencies, which can intensify radical production pathways and increase atmospheric oxidative capacity (Lee et al., 2006; Wang et al., 2026d,e). Enhanced photolysis of HONO, O₃ photolysis followed by reactions of excited-state oxygen atoms O(¹D) with water vapor, and photolysis of HCHO and other OVOCs all serve as the primary sources of OH and HO₂ radicals during heatwaves (Ma et al., 2022; Pu et al., 2017; Wang et al., 2026g; Ye et al., 2023). Field observations and observation-constrained box modeling in Xuzhou revealed that major primary radical sources, including photolysis of HONO, O₃, HCHO, and other OVOCs, increased by ~64.7% during heatwave periods compared with normal temperature conditions (Zhang et al., 2024a). Similarly, WRF-CMAQ simulations of the 2022 extreme heatwave in China showed enhanced OH and HO₂ concentrations under heatwave meteorology compared to the summer of 2021 (Wang et al., 2026d). The elevated radical supply promotes VOC oxidation via the RO₂/HO₂-NO_x cycle, accelerates NO-to-NO₂ conversion, sustains radical regeneration, and ultimately increases net O₃ production rates (Lee et al., 2006; Meng et al., 2023).

However, whether enhanced VOC oxidation and radical cycling translate into net O₃ accumulation



depends strongly on the relative availability of VOCs and NO_x and the prevailing O₃ formation regime
775 (Kleinman, 1994; Wang et al., 2019; Zhou et al., 2026). Under VOC-limited conditions, where NO_x is
relatively abundant, additional VOCs introduced during heatwaves can substantially enhance O₃
production (Huang et al., 2025; Liu et al., 2026a; Wang et al., 2025). In contrast, under NO_x-limited
conditions, insufficient NO availability restricts the conversion of newly formed peroxy radicals into
NO₂, thereby reducing the marginal contribution of additional VOCs to O₃ formation (Coates et al.,
780 2016; Sillman, 1999; Wang et al., 2019; Whalley et al., 2021). Heatwaves can dynamically reshape O₃
formation regimes by altering VOC-NO_x balance and radical budgets (Li et al., 2024; Pusede and
Cohen, 2012). Previous studies have shown that in many urban and regional environments, increases
in VOC reactivity during heatwaves can exceed changes in effective NO_x availability, causing O₃
formation regimes to shift from VOC-limited toward transitional or NO_x-limited conditions, thereby
785 reducing the marginal effect of additional VOC emissions on O₃ production (Huang et al., 2025; Li et
al., 2025b; Liu et al., 2026a; Zhou et al., 2026). For example, Recent studies investigating climate
warming impacts on O₃ formation further suggest that heatwave-induced PAN thermal decomposition
and changes in radical termination pathways can alter the balance between radicals and NO_x, together
with enhanced BVOC emissions, promoting shifts toward NO_x-limited regimes (Porter and Heald,
790 2019; Wang et al., 2026f,g). However, this transition is not always unidirectional, as enhanced soil NO
emissions during heatwaves may partially offset NO_x limitation and amplify the contribution of
BVOCs to O₃ formation (Yang et al., 2026b).

Beyond local emissions and chemical processes, boundary layer dynamics and regional transport
strongly modulate the vertical and horizontal distributions of VOC precursors and O₃, resulting in
795 pronounced spatial and temporal variations in O₃ formation regimes under heatwave conditions (Pan
et al., 2026; Wang et al., 2021a). Zhou et al. (2025) found that heatwaves can decrease near-surface
NO_x while increasing upper-level NO_x concentrations, leading to vertical differences in O₃ sensitivity
and photochemical intensity and promoting column-integrated O₃ enhancement. Comparisons between
heatwave-O₃ compound events and isolated heatwave events further reveal that boundary layer
800 stability, ventilation conditions, and vertical mixing determine whether locally produced O₃
accumulates or is transported regionally (Pan et al., 2026). Moreover, enhanced BVOC emissions and
their oxidation products during heatwaves can be transported to downwind VOC-limited regions,



supplying reactive organic precursors and sustaining regional O₃ formation (Wang et al., 2021a).

805 **7.3 Mechanisms and controlling factors of VOC-to-SOA transformation under heatwave**

The transformation of VOCs into SOA involves a series of coupled processes, including gas-phase oxidation, formation of low-volatility products, gas-particle partitioning, and multiphase reactions (Kroll and Seinfeld, 2008; Shen et al., 2024; Zeng et al., 2026b). VOCs and IVOCs undergo oxidation by OH, O₃, or NO₃ radicals, producing oxygenated organic compounds with a wide range of volatilities (Bianchi et al., 2019; Presto et al., 2009; Srivastava et al., 2022). These oxidation products subsequently enter and remain in the particle phase via condensation, absorptive partitioning, or reactive uptake, contributing to SOA formation and mass growth (Nie et al., 2022; Pankow, 1994). Among these products, semi-volatile organic compounds (SVOCs) dynamically partition between the gas and particle phases, whereas low-volatility organic compounds (LVOCs) and extremely low-volatility organic compounds (ELVOCs) tend to condense onto particles. In addition, water-soluble or highly reactive products can undergo further multiphase reactions to form less volatile compounds (Donahue et al., 2006; Ehn et al., 2014; McNeill, 2015). Current studies suggest that heatwaves generally promote SOA formation by increasing emissions of temperature-sensitive precursors and accelerating photochemical oxidation, although this enhancement is strongly modulated by gas-particle partitioning, particle-phase transformation, and SOA retention processes (Aas et al., 2026; Deng et al., 2021).

Enhanced precursor availability and oxidative capacity are primary drivers of heatwave-induced SOA formation (Aas et al., 2026; Wang et al., 2026d; Zhang et al., 2024c). Heatwaves can increase emissions of temperature-sensitive VOCs and S/IVOCs and enhance atmospheric oxidative capacity through elevated OH radical concentrations under strong solar radiation, thereby accelerating the conversion of organic precursors into oxygenated products with lower volatility and increasing the supply of condensable species required for SOA formation (Hass-Mitchell et al., 2024; Pfannerstill et al., 2024; Wang et al., 2026d). Studies across China, the United States, and Europe have demonstrated that enhanced precursor emissions and oxidation during heatwaves can elevate SOA formation potential or ambient SOA concentrations, although the magnitude and chemical composition of these responses vary considerably among regions and atmospheric environments (Wang et al., 2026e; Yin et al., 2026;



Zhang et al., 2024c). Furthermore, RO₂ radicals generated from VOC oxidation can undergo autoxidation to form HOMs, while reactions between RO₂ and other radicals can generate low-volatility products that promote SOA formation (Baker et al., 2024; Nie et al., 2023; Zeng et al., 2026b).

835 However, experimental studies indicate that these pathways are strongly regulated by temperature and the competition between RO₂ reactions with NO, HO₂, and other RO₂ radicals (Baker et al., 2024; Yang et al., 2025).

However, SOA formation does not increase proportionally with VOC oxidation, because SOA production efficiency is also controlled by the fraction of low-volatility products generated during oxidation and their ability to partition into the particle phase (Cai et al., 2024b; Lannuque et al., 2023; Zuend and Seinfeld, 2012). Among these processes, gas-particle partitioning of semi-volatile oxidation products is a critical factor controlling SOA mass changes under heatwave conditions (Aas et al., 2026; Odum et al., 1996; Zuend and Seinfeld, 2012). The particle-phase fraction of organic oxidation products is primarily governed by their effective saturation concentration (C_i^*), the available organic aerosol mass concentration for absorption, and particle-phase activity coefficients (Pankow, 1994; Serrano Damha et al., 2024; Shiraiwa and Pöschl, 2021). Rising temperature generally elevates C_i^* , promoting the evaporation of SVOCs from particles back into the gas phase and thereby reducing SOA mass. In contrast, LVOCs and ELVOCs are more efficiently retained in the particle phase and exhibit weaker responses to temperature-driven partitioning changes (Deng et al., 2021; Shahin et al., 2025).

845 For instance, Lannuque et al. (2023) conducted simultaneous gas- and particle- phase molecular measurements of toluene photooxidation products and found that decreasing temperature increased organic aerosol mass, while the fraction of toluene-derived carbon partitioning into particles increased from approximately 1% to 3%. Aas et al. (2026) explicitly represented gas-particle partitioning of 1223 semi-volatile and low-volatility oxidation products in simulations of the 2022 European heatwave and

855 demonstrated that SOA responses during heatwave periods depend strongly on precursor identity.

Reactive uptake and particle-phase reactions are critical pathways that mediate the conversion and atmospheric persistence of gas-phase oxidation products into SOA (Schmedding et al., 2020; Shiraiwa and Pöschl, 2021; Zeng et al., 2026b). Water-soluble species such as isoprene epoxydiols (IEPOX) and glyoxal can undergo reactive uptake into aqueous aerosol particles, followed by acid-catalyzed



860 reactions, oligomerization, and organosulfate formation, generating lower-volatility compound
(Battaglia et al., 2025; D'Ambro et al., 2017; Hu et al., 2022; Kim et al., 2022; Tilgner et al., 2021).
These processes are commonly characterized using reactive uptake coefficients (γ), which are jointly
controlled by temperature, relative humidity, aerosol acidity, and other environmental factors (Gaston
et al., 2014; Schmedding et al., 2020; Zhang et al., 2018; Zhu et al., 2025). Under heatwave conditions,
865 rising temperature can enhance molecular diffusion and accelerate certain particle-phase reactions, but
it can also reduce gas solubility and promote evaporation of semi-volatile components (Li and Knopf,
2021; Pye et al., 2020; Zeng et al., 2026b; Zhang et al., 2023). Furthermore, aerosol viscosity and
intraparticle diffusion processes provide additional controls on SOA formation and persistence
(DeRieux et al., 2018; Kiland et al., 2022). Under heatwave conditions, temperature increases
870 generally decrease aerosol viscosity and accelerate molecular diffusion, whereas reductions in relative
humidity and aerosol liquid water content may increase particle viscosity, potentially offsetting or even
reversing the direct effects of warming (Hao et al., 2025; Li and Shiraiwa, 2019; Schervish and
Shiraiwa, 2023; Shiraiwa and Pöschl, 2021).

8 Summary and outlook

875 This review synthesizes current understanding of how heatwaves affect ambient VOC composition,
anthropogenic and biogenic sources, atmospheric transformation, and the formation of O₃ and SOA.
Available observations generally indicate that total ambient VOC concentrations increase during
heatwaves, although the dominant compounds and their responses vary considerably among cities
because of differences in emission sources, ecosystem types, and meteorological conditions.
880 Temperature-sensitive anthropogenic sources, including solvent use, volatile chemical products, fuel
storage, and vehicle evaporation, often respond strongly to elevated temperatures, whereas
combustion-related emissions are less directly temperature dependent. Biogenic emissions,
particularly isoprene and monoterpenes, exhibit nonlinear responses governed by temperature, plant
physiology, water availability, and species-specific storage and synthesis pathways. Ambient VOC
885 responses therefore reflect the combined effects of emission changes, atmospheric transport, and
chemical processing rather than temperature alone.

Heatwaves also modify the atmospheric fate of VOCs. Increased photolysis and radical production can



enhance atmospheric oxidation and alter VOC reaction pathways and radical cycling. However, the resulting O₃ and SOA responses are not uniform. O₃ formation depends strongly on VOC composition and formation regimes, as well as temperature-dependent processes such as PAN decomposition. SOA formation and persistence are further regulated by oxidation-product volatility, gas–particle partitioning, reactive uptake, and particle-phase diffusion. Field observations, smog chamber and reactor experiments, box models and process-based models, and chemical transport models provide complementary evidence for these processes.

Future research should improve the identification and attribution of heatwave-induced changes in VOC sources. Continuous measurements covering complete heatwave events remain scarce, while transport and chemical processing can obscure emission signals in ambient concentrations. Coordinated studies across multiple events and regions should combine high-time-resolution VOC observations, flux measurements, source apportionment, satellite constraints, and inverse modeling. Such integration would help distinguish emission changes from atmospheric processing, quantify source-specific temperature responses, and evaluate whether emission parameterizations developed for one region or ecosystem can be transferred to others.

Further work is also needed to determine how heatwaves alter VOC processing and secondary pollutant formation under real atmospheric conditions. Field observations should be combined with chamber experiments, process-level models, and regional chemical transport models to quantify the relative contributions of enhanced emissions, altered oxidant levels, radical chemistry, and temperature-dependent reaction pathways. Particular attention should be given to interactions among VOC composition, NO_x regimes, atmospheric oxidizing capacity, and multiphase processes. Resolving these interactions will improve mechanistic understanding and strengthen predictions of VOC-driven O₃ and SOA pollution during increasingly frequent and severe heatwave events.

Code and data availability

No code was used; data were taken from the publications listed in the Supplement.

Supplement



915 The supplement related to this article is available online.

Author contributions

Wenqi Liu performed formal analysis, wrote the original draft, and reviewed and edited the manuscript;
Jin Wang performed formal analysis, wrote the original draft, and reviewed and edited the manuscript;
920 Baoshuang Liu conceptualized the study, wrote the original draft, and reviewed and edited the
manuscript; Litao Wang reviewed and edited the manuscript; Shaojie Song conceptualized the study,
performed formal analysis, wrote the original draft, and reviewed and edited the manuscript; Yinchang
Feng reviewed and edited the manuscript.

Competing interests

925 The contact author has declared that none of the authors has any competing interests.

Disclaimer

Publisher's note: Copernicus Publications remains neutral with regard to jurisdictional claims made in
930 the text, published maps, institutional affiliations, or any other geographical representation in this paper.
While Copernicus Publications makes every effort to include appropriate place names, the final
responsibility lies with the authors. Views expressed in the text are those of the authors and do not
necessarily reflect the views of the publisher.

Acknowledgements

935 This work was supported by the Jing-Jin-Ji Regional Integrated Environmental Improvement-National
Science and Technology Major Project (No. 2026ZD1209700), National Natural Science Foundation
of China (No. 42477101), Tianjin Natural Science Foundation Project (No. 25JCYBJC01390), and the
Fundamental Research Funds for the Central Universities (No. 040-63261157).

940

References

Aas, W., Salameh, T., Wegener, R., Hellén, H., Jaffrezo, J.-L., Roldin, P., Alonso-Blanco, E., Alastuey, A., Amelynck,
C., Arduini, J., Bergmans, B., Bertrand, M., Borbon, A., Bourtsoukidis, E., Bouvier, L., Butterfield, D., Buxbaum, I.,
Ceburnis, D., Claude, A., Colette, A., Colomb, A., Darfeuil, S., Dernie, J., Desservettaz, M., Díaz-Ramiro, E.,



- 945 Dufresne, M., Dubus, R., Duval, M., Dury, M., Font, A., Fossum, K. N., Freney, E., Gangoiti, G., Ge, Y., Gomez, M. C., Gómez-Moreno, F. J., Gohy, M., Gros, V., Hamer, P., Hellack, B., Hermann, H., Holla, R., Holubová, A., Jensen, N. R., Jokinen, T., Jones, M., Käfer, U., Kesper, L., Klemp, D., Kubistin, D., Marinoni, A., Mazzini, M., Thuy Dinh, V. N., Ovadnevaite, J., Petäjä, T., Portillo-Estrada, M., Přivozníková, J., Putaud, J.-P., Reimann, S., Renzi, L., Riffault, V., Ritchie, S., Robins, C., Rodríguez de Torres, B. A., Poulain, L., Rüdiger, J., Sanocka, A., Saez de Camara Oleaga, E., Schoon, N., Seco, R., Simmons, I., Simon, L., Simpson, D., Solberg, S., Tison, E., Thomasson, A., Tsyro, S., Twigg, M., Tykkä, T., Verreyken, B., Watne, Å., Williams, K., Yáñez-Serrano, A. M., Yeung, K., Ylivinkka, I., and Yttri, K. E.: Measurement report: Spatial variability of VOCs, ozone, and carbonaceous aerosols during the 2022 European summer heatwave, *Atmos. Chem. Phys.*, 26, 8717–8751, <https://doi.org/10.5194/acp-26-8717-2026>, 2026.
- 950 Adeyeri, O. E., Zhou, W., Ndehedehe, C. E., Ishola, K. A., Laux, P., Akinsanola, A. A., Dieng, M. D. B., and Wang, X.: Global Heatwaves Dynamics Under Climate Change Scenarios: Multidimensional Drivers and Cascading Impacts, *Earths Future*, 13, e2025EF006486, <https://doi.org/10.1029/2025EF006486>, 2025.
- Agencia Estatal de Meteorología (AEMET): Olas de calor en España desde 1975, Agencia Estatal de Meteorología, https://www.aemet.es/en/conocerlas/recursos_en_linea/publicaciones_y_estudios/estudios/detalles/olascalor (last access: 14 September 2026), 2024.
- 960 Angot, H., McErlean, K., Hu, L., Millet, D. B., Hueber, J., Cui, K., Moss, J., Wielgasz, C., Milligan, T., Ketcherside, D., Bret-Harte, M. S., and Helmig, D.: Biogenic volatile organic compound ambient mixing ratios and emission rates in the Alaskan Arctic tundra, *Biogeosciences*, 17, 6219–6236, <https://doi.org/10.5194/bg-17-6219-2020>, 2020.
- Atkinson, R.: Atmospheric chemistry of VOCs and NO_x, *Atmos. Environ.*, 34, 2063–2101, [https://doi.org/https://doi.org/10.1016/S1352-2310\(99\)00460-4](https://doi.org/https://doi.org/10.1016/S1352-2310(99)00460-4), 2000.
- 965 Atkinson, R. and Arey, J.: Atmospheric Degradation of Volatile Organic Compounds, *Chem. Rev.*, 103, 4605–4638, <https://doi.org/10.1021/cr0206420>, 2003.
- Baker, Y., Kang, S., Wang, H., Wu, R., Xu, J., Zanders, A., He, Q., Hohaus, T., Ziehm, T., Geretti, V., Bannan, T. J., O'Meara, S. P., Voliotis, A., Hallquist, M., McFiggans, G., Zorn, S. R., Wahner, A., and Mentel, T. F.: Impact of HO₂/RO₂ ratio on highly oxygenated α -pinene photooxidation products and secondary organic aerosol formation potential, *Atmos. Chem. Phys.*, 24, 4789–4807, <https://doi.org/10.5194/acp-24-4789-2024>, 2024.
- 970 Bamberger, I., Ruehr, N. K., Schmitt, M., Gast, A., Wohlfahrt, G., and Arneth, A.: Isoprene emission and photosynthesis during heatwaves and drought in black locust, *Biogeosciences*, 14, 3649–3667, <https://doi.org/10.5194/bg-14-3649-2017>, 2017.
- Bao, Q., Wu, L., Wang, Y., Su, R., Wang, Z., Tan, Z., Dai, L., Wang, P., Guo, E., and Sun, Z.: Response of gross primary productivity to compound drought–heat events in southeast asian rubber plantations, *J. Hydrol. Reg. Stud.*, 66, 103632, <https://doi.org/10.1016/j.ejrh.2026.103632>, 2026.
- 975 Barriopedro, D., García-Herrera, R., Ordóñez, C., Miralles, D. G., and Salcedo-Sanz, S.: Heat Waves: Physical Understanding and Scientific Challenges, *Rev. Geophys.*, 61, e2022RG000780, <https://doi.org/10.1029/2022RG000780>, 2023.
- 980 Battaglia, F., Formenti, P., Giorio, C., Cazaunau, M., Pangui, E., Bergé, A., Gratien, A., Pereira, D. L., Bertin, T., de Brito, J. F., Romanias, M. N., Michoud, V., Baldo, C., Chevaillier, S., Noyalet, G., Decorse, P., Picquet-Varrault, B.,



- and Doussin, J.-F.: Formation and composition of organic aerosols from the uptake of glyoxal on natural mineral dust aerosols: a laboratory study, *Atmos. Chem. Phys.*, 25, 12409–12431, <https://doi.org/10.5194/acp-25-12409-2025>, 2025.
- 985 Bauwens, M., Stavrou, T., Müller, J.-F., De Smedt, I., Van Roozendaal, M., van der Werf, G. R., Wiedinmyer, C., Kaiser, J. W., Sindelarova, K., and Guenther, A.: Nine years of global hydrocarbon emissions based on source inversion of OMI formaldehyde observations, *Atmos. Chem. Phys.*, 16, 10133–10158, <https://doi.org/10.5194/acp-16-10133-2016>, 2016.
- 990 Bekris, Y. S., Ting, M., Singh, D., and Kalashnikov, D. A.: Distinct Characteristics of Contiguous Heatwaves Across Terrestrial, Marine, and Coastal Environments, *Geophys. Res. Lett.*, 53, e2025GL118531, <https://doi.org/10.1029/2025GL118531>, 2026.
- Bhattarai, S., Bokati, L., Sharma, S., and Talchabhadel, R.: Understanding spatiotemporal variation of heatwave projections across US cities, *Sci. Rep.*, 15, 10643, <https://doi.org/10.1038/s41598-025-95097-5>, 2025.
- 995 Bi, P., Chen, X., Pan, Z., Huang, N., Gao, R., Men, J., Wu, C., Zhang, F., Huang, Z., Gao, E., Yao, Y., and Long, B.: Increasing global heatwave occurrence associated with land-atmosphere interactions, *Npj Clim. Atmos. Sci.*, 9, 89, <https://doi.org/10.1038/s41612-026-01356-1>, 2026.
- Bian, Y., Sun, P., Zhang, Q., Luo, M., and Liu, R.: Amplification of non-stationary drought to heatwave duration and intensity in eastern China: Spatiotemporal pattern and causes, *J. Hydrol.*, 612, 128154, <https://doi.org/10.1016/j.jhydrol.2022.128154>, 2022.
- 1000 Bianchi, F., Kurtén, T., Riva, M., Mohr, C., Rissanen, M. P., Roldin, P., Berndt, T., Crounse, J. D., Wennberg, P. O., Mentel, T. F., Wildt, J., Junninen, H., Jokinen, T., Kulmala, M., Worsnop, D. R., Thornton, J. A., Donahue, N., Kjaergaard, H. G., and Ehn, M.: Highly Oxygenated Organic Molecules (HOM) from Gas-Phase Autoxidation Involving Peroxy Radicals: A Key Contributor to Atmospheric Aerosol, *Chem. Rev.*, 119, 3472–3509, <https://doi.org/10.1021/acs.chemrev.8b00395>, 2019.
- 1005 Birami, B., Bamberger, I., Ghirardo, A., Grote, R., Arneeth, A., Gaona-Colmán, E., Nadal-Sala, D., and Ruehr, N. K.: Heatwave frequency and seedling death alter stress-specific emissions of volatile organic compounds in Aleppo pine, *Oecologia*, 197, 939–956, <https://doi.org/10.1007/s00442-021-04905-y>, 2021.
- Boboc, L., Dima, M., Vaideanu, P., and Ionita, M.: Trends and variability of heat waves in Europe and the association with large-scale circulation patterns, *Weather Clim. Extrem.*, 49, 100794, <https://doi.org/https://doi.org/10.1016/j.wace.2025.100794>, 2025.
- 1010 Bourtsoukidis, E., Bonn, B., Dittmann, A., Hakola, H., Hellén, H., and Jacobi, S.: Ozone stress as a driving force of sesquiterpene emissions: a suggested parameterisation, *Biogeosciences*, 9, 4337–4352, <https://doi.org/10.5194/bg-9-4337-2012>, 2012.
- 1015 Bourtsoukidis, E., Pozzer, A., Williams, J., Makowski, D., Peñuelas, J., Matthaïos, V. N., Lazoglou, G., Yañez-Serrano, A. M., Lelieveld, J., Ciais, P., Vrekoussis, M., Daskalakis, N., and Sciare, J.: High temperature sensitivity of monoterpene emissions from global vegetation, *Commun. Earth Environ.*, 5, 23, <https://doi.org/10.1038/s43247-023-01175-9>, 2024.



- 1020 Bourtsoukidis, E., Guenther, A., Wang, H., Economou, T., Lazoglou, G., Christodoulou, A., Christoudias, T., Nölscher, A., Yañez-Serrano, A. M., and Peñuelas, J.: Environmental Change Is Reshaping the Temperature Sensitivity of Sesquiterpene Emissions and Their Atmospheric Impacts, *Glob. Change Biol.*, 31, e70258, <https://doi.org/https://doi.org/10.1111/gcb.70258>, 2025.
- Bunting, E. L., Tolmanov, V., and Keellings, D.: What is a heat wave: A survey and literature synthesis of heat wave definitions across the United States, *PLOS Clim.*, 3, e0000468, <https://doi.org/10.1371/journal.pclm.0000468>, 2024.
- 1025 Cai, F., Liu, C., Gerten, D., Yang, S., Zhang, T., Lin, S., and Kurths, J.: Pronounced spatial disparity of projected heatwave changes linked to heat domes and land-atmosphere coupling, *Npj Clim. Atmos. Sci.*, 7, 225, <https://doi.org/10.1038/s41612-024-00779-y>, 2024a.
- Cai, M., Ye, C., Yuan, B., Huang, S., Zheng, E., Yang, S., Wang, Z., Lin, Y., Li, T., Hu, W., Chen, W., Song, Q., Li, W., Peng, Y., Liang, B., Sun, Q., Zhao, J., Chen, D., Sun, J., Yang, Z., and Shao, M.: Enhanced daytime secondary aerosol formation driven by gas–particle partitioning in downwind urban plumes, *Atmos. Chem. Phys.*, 24, 13065–13079, <https://doi.org/10.5194/acp-24-13065-2024>, 2024b.
- 1030 Carter, W. P. L.: Development of the SAPRC-07 chemical mechanism, *Atmos. Environ.*, 44, 5324–5335, <https://doi.org/https://doi.org/10.1016/j.atmosenv.2010.01.026>, 2010.
- Carter, W. P. L., Pierce, J. A., Luo, D., and Malkina, I. L.: Environmental chamber study of maximum incremental reactivities of volatile organic compounds, *Atmos. Environ.*, 29, 2499–2511, [https://doi.org/https://doi.org/10.1016/1352-2310\(95\)00149-S](https://doi.org/https://doi.org/10.1016/1352-2310(95)00149-S), 1995.
- 1035 Carter, W. P. L., Winer, A. M., Darnall, K. R., and Pitts, Jr., James N.: Smog chamber studies of temperature effects in photochemical smog, *Environ. Sci. Technol.*, 13, 1094–1100, <https://doi.org/10.1021/es60157a006>, 2002.
- Ceccherini, G., Russo, S., Amezttoy, I., Marchese, A. F., and Carmona-Moreno, C.: Heat waves in Africa 1981–2015, observations and reanalysis, *Nat. Hazards Earth Syst. Sci.*, 17, 115–125, <https://doi.org/10.5194/nhess-17-115-2017>, 2017.
- 1040 Chace, W. S., Womack, C., Ball, K., Bates, K. H., Bohn, B., Coggon, M., Crounse, J. D., Fuchs, H., Gilman, J., Gkatzelis, G. I., Jernigan, C. M., Novak, G. A., Novelli, A., Peischl, J., Pollack, I., Robinson, M. A., Rollins, A., Schafer, N. B., Schwantes, R. H., Selby, M., Stainsby, A., Stockwell, C., Taylor, R., Treadaway, V., Veres, P. R., Warneke, C., Waxman, E., Wennberg, P. O., Wolfe, G. M., Xu, L., Zuraski, K., and Brown, S. S.: Ozone Production Efficiencies in the Three Largest United States Cities from Airborne Measurements, *Environ. Sci. Technol.*, 59, 13306–13318, <https://doi.org/10.1021/acs.est.5c02073>, 2025.
- 1045 Chen, J., Tang, J., Rinnan, R., and Zhu, B.: Global Variability in Isoprenoid Emissions: Divergent Responses to Warming and Drought Driven by Physiochemical Controls, *Plant Cell Environ.*, 49, 5294–5312, <https://doi.org/https://doi.org/10.1111/pce.70536>, 2026.
- 1050 Chen, L. and Wang, K.: Can global weather station network capture heatwaves?, *Atmos. Res.*, 327, 108335, <https://doi.org/10.1016/j.atmosres.2025.108335>, 2026.
- Chen, Q., Miao, R., Geng, G., Shrivastava, M., Dao, X., Xu, B., Sun, J., Zhang, X., Liu, M., Tang, G., Tang, Q., Hu, H., Huang, R.-J., Wang, H., Zheng, Y., Qin, Y., Guo, S., Hu, M., and Zhu, T.: Widespread 2013–2020 decreases and



- 1055 reduction challenges of organic aerosol in China, *Nat. Commun.*, 15, 4465, <https://doi.org/10.1038/s41467-024-48902-0>, 2024a.
- Chen, R., Wen, Z., Lin, W., and Qiao, Y.: Diverse relationship between the tropical night in South China and the water vapor transport over the South China Sea and the plausible causes, *Atmos. Res.*, 296, 107080, <https://doi.org/10.1016/j.atmosres.2023.107080>, 2023.
- 1060 Chen, T., Wang, T., Xue, L., and Brasseur, G.: Heatwave exacerbates air pollution in China through intertwined climate-energy-environment interactions, *Sci. Bull.*, 69, 2765–2775, <https://doi.org/https://doi.org/10.1016/j.scib.2024.05.018>, 2024b.
- Chen, W., Xu, X., and Liu, W.: Combined PMF modelling and machine learning to identify sources and meteorological influencers of volatile organic compound pollution in an industrial city in eastern China, *Atmos. Environ.*, 334, 120714, <https://doi.org/https://doi.org/10.1016/j.atmosenv.2024.120714>, 2024c.
- 1065 Chen, X.: Significant Increases in Wet Nighttime and Daytime–Nighttime Compound Heat Waves in China from 1961 to 2020, *Atmosphere*, 14, 178, <https://doi.org/10.3390/atmos14010178>, 2023.
- Chen, Y. and Li, Y.: An Inter-comparison of Three Heat Wave Types in China during 1961–2010: Observed Basic Features and Linear Trends, *Sci. Rep.*, 7, 45619, <https://doi.org/10.1038/srep45619>, 2017.
- 1070 Chen, Z.-Y., Petetin, H., Méndez Turrubiates, R. F., Achebak, H., Pérez García-Pando, C., and Ballester, J.: Population exposure to multiple air pollutants and its compound episodes in Europe, *Nat. Commun.*, 15, 2094, <https://doi.org/10.1038/s41467-024-46103-3>, 2024d.
- China Meteorological Administration (CMA): High Temperature, China Meteorological Administration, https://www.cma.gov.cn/2011xzt/kpbd/heatwave/2018050901/201807/t20180709_472855.html (last access: 14 September 2026), 2018.
- 1075 Chu, C., Liang, J., Sun, X., Zhong, S., Fang, J., and Lu, W.: Characteristics and mechanisms of typical ozone pollution episode during heat waves in Jiangsu Province, *J. Meteorol. Sci.*, 42, 742–753, 2022.
- Churkina, G., Kuik, F., Bonn, B., Lauer, A., Grote, R., Tomiak, K., and Butler, T. M.: Effect of VOC Emissions from Vegetation on Air Quality in Berlin during a Heatwave, *Environ. Sci. Technol.*, 51, 6120–6130, <https://doi.org/10.1021/acs.est.6b06514>, 2017.
- 1080 Coates, J., Mar, K. A., Ojha, N., and Butler, T. M.: The influence of temperature on ozone production under varying NO_x conditions – a modelling study, *Atmos. Chem. Phys.*, 16, 11601–11615, <https://doi.org/10.5194/acp-16-11601-2016>, 2016.
- Comeau, É., Di Luca, A., and Kirchmeier-Young, M.: From mild to extreme heatwaves: Examining trends in North America, *Weather Clim. Extrem.*, 51, 100831, <https://doi.org/10.1016/j.wace.2025.100831>, 2026.
- 1085 Conti, A., Valente, M., Paganini, M., Farsoni, M., Ragazzoni, L., and Barone-Adesi, F.: Knowledge Gaps and Research Priorities on the Health Effects of Heatwaves: A Systematic Review of Reviews, *Int. J. Environ. Res. Public Health*, 19, 5887, <https://doi.org/10.3390/ijerph19105887>, 2022.



- 1090 Contreras-Serrano, M., Lindsby, N., Rinnan, R., Duegaard, E. C. N., Rosenqvist, E., Chen, S., Fu, Y. H., and Tang, J.: Increased Growth Temperatures Alter Arctic Plant Responses to Heat Wave and Drought, *Glob. Change Biol.*, 31, e70187, <https://doi.org/https://doi.org/10.1111/gcb.70187>, 2025.
- Cui, Y., Liu, B., Yang, Y., Kang, S., Wang, F., Xu, M., Wang, W., Feng, Y., and Hopke, P. K.: Primary and oxidative source analyses of consumed VOCs in the atmosphere, *J. Hazard. Mater.*, 476, 134894, <https://doi.org/https://doi.org/10.1016/j.jhazmat.2024.134894>, 2024.
- 1095 D'Ambro, E. L., Lee, B. H., Liu, J., Shilling, J. E., Gaston, C. J., Lopez-Hilfiker, F. D., Schobesberger, S., Zaveri, R. A., Mohr, C., Lutz, A., Zhang, Z., Gold, A., Surratt, J. D., Rivera-Rios, J. C., Keutsch, F. N., and Thornton, J. A.: Molecular composition and volatility of isoprene photochemical oxidation secondary organic aerosol under low- and high-NO_x conditions, *Atmos. Chem. Phys.*, 17, 159–174, <https://doi.org/10.5194/acp-17-159-2017>, 2017.
- Dawson, J. P., Adams, P. J., and Pandis, S. N.: Sensitivity of PM_{2.5} to climate in the Eastern US: a modeling case study, *Atmos. Chem. Phys.*, 7, 4295–4309, <https://doi.org/10.5194/acp-7-4295-2007>, 2007.
- 1100 De Paula Corrêa, M.: Heatwaves, biodiversity and health in times of climate change, *J. Pediatr. (Rio J.)*, 101, S27–S33, <https://doi.org/10.1016/j.jped.2024.10.002>, 2025.
- Debevec, C., Sauvage, S., Gros, V., Salameh, T., Sciare, J., Dulac, F., and Locoge, N.: Seasonal variation and origins of volatile organic compounds observed during 2 years at a western Mediterranean remote background site (Ersa, Cape Corsica), *Atmos. Chem. Phys.*, 21, 1449–1484, <https://doi.org/10.5194/acp-21-1449-2021>, 2021.
- 1105 Deng, K.-Q., Azorin-Molina, C., Yang, S., Hu, C.-D., Zhang, G.-F., Minola, L., Vicente-Serrano, S., and Chen, D.: Shifting of summertime weather extremes in Western Europe during 2012–2020, *Adv. Clim. Change Res.*, 13, 218–227, <https://doi.org/10.1016/j.accre.2022.01.008>, 2022.
- Deng, Y., Inomata, S., Sato, K., Ramasamy, S., Morino, Y., Enami, S., and Tanimoto, H.: Temperature and acidity dependence of secondary organic aerosol formation from α -pinene ozonolysis with a compact chamber system, *Atmos. Chem. Phys.*, 21, 5983–6003, <https://doi.org/10.5194/acp-21-5983-2021>, 2021.
- 1110 DeRieux, W.-S. W., Li, Y., Lin, P., Laskin, J., Laskin, A., Bertram, A. K., Nizkorodov, S. A., and Shiraiwa, M.: Predicting the glass transition temperature and viscosity of secondary organic material using molecular composition, *Atmos. Chem. Phys.*, 18, 6331–6351, <https://doi.org/10.5194/acp-18-6331-2018>, 2018.
- 1115 Deutscher Wetterdienst (DWD): Data Set Description – Historical Heat Alerts, Deutscher Wetterdienst, https://opendata.dwd.de/climate_environment/health/historical_alerts/heat_warnings/Description_historical_heat_alerts.pdf (last access: 14 September 2026), 2024.
- Diao, L., Liu, B., Meng, H., Shi, L., Feng, Y., Zhang, J., and Hopke, P. K.: Effects of High Temperatures on the Consumed VOCs Derived from Multiple Urban Emission Sources, *ACS EST Air*, 2, 2105–2116, <https://doi.org/10.1021/acsestair.5c00111>, 2025.
- 1120 Ding, T., Gao, H., and Xie, T.: Obvious difference of dominant circulation patterns between dry-type and humid-type heatwaves in North China, *Int. J. Climatol.*, 44, 4710–4724, <https://doi.org/10.1002/joc.8605>, 2024.
- Donahue, N. M., Robinson, A. L., Stanier, C. O., and Pandis, S. N.: Coupled Partitioning, Dilution, and Chemical



- Aging of Semivolatile Organics, *Environ. Sci. Technol.*, 40, 2635–2643, <https://doi.org/10.1021/es052297c>, 2006.
- 1125 Dufresne, M., Salameh, T., Leonardis, T., Gille, G., Armengaud, A., and Sauvage, S.: Volatile organic compound sources and impacts in an urban Mediterranean area (Marseille, France), *Atmos. Chem. Phys.*, 25, 5977–5999, <https://doi.org/10.5194/acp-25-5977-2025>, 2025.
- 1130 Ehn, M., Thornton, J. A., Kleist, E., Sipilä, M., Junninen, H., Pullinen, I., Springer, M., Rubach, F., Tillmann, R., Lee, B., Lopez-Hilfiker, F., Andres, S., Acir, I.-H., Rissanen, M., Jokinen, T., Schobesberger, S., Kangasluoma, J., Kontkanen, J., Nieminen, T., Kurtén, T., Nielsen, L. B., Jørgensen, S., Kjaergaard, H. G., Canagaratna, M., Maso, M. D., Berndt, T., Petäjä, T., Wahner, A., Kerminen, V.-M., Kulmala, M., Worsnop, D. R., Wildt, J., and Mentel, T. F.: A large source of low-volatility secondary organic aerosol, *Nature*, 506, 476–479, <https://doi.org/10.1038/nature13032>, 2014.
- 1135 Elshorbany, Y., Ziemke, J. R., Strode, S., Petetin, H., Miyazaki, K., De Smedt, I., Pickering, K., Seguel, R. J., Worden, H., Emmerichs, T., Taraborrelli, D., Cazorla, M., Fadnavis, S., Buchholz, R. R., Gaubert, B., Rojas, N. Y., Nogueira, T., Salameh, T., and Huang, M.: Tropospheric ozone precursors: global and regional distributions, trends, and variability, *Atmos. Chem. Phys.*, 24, 12225–12257, <https://doi.org/10.5194/acp-24-12225-2024>, 2024.
- European Environment Agency (EEA): EMEP/EEA air pollutant emission inventory guidebook 2019, European Environment Agency, Copenhagen, <https://www.eea.europa.eu/publications/emep-eea-guidebook-2019> (last access: 27 July 2026), 2019.
- 1140 Feng, J., Li, J., Jin, F.-F., Zhao, S., and Li, J.: Anthropogenic forcing drives equatorward migration of heatwave locations across continents, *Nat. Commun.*, 16, 8197, <https://doi.org/10.1038/s41467-025-63558-0>, 2025.
- Feng, S., Jiang, F., Qian, T., Wang, N., Jia, M., Zheng, S., Chen, J., Ying, F., and Ju, W.: Constraining non-methane VOC emissions with TROPOMI HCHO observations: impact on summertime ozone simulation in August 2022 in China, *Atmos. Chem. Phys.*, 24, 7481–7498, <https://doi.org/10.5194/acp-24-7481-2024>, 2024.
- 1145 Ferracci, V., Bolas, C. G., Freshwater, R. A., Staniaszek, Z., King, T., Jaars, K., Otu-Larbi, F., Beale, J., Malhi, Y., Waite, T. W., Jones, R. L., Ashworth, K., and Harris, N. R. P.: Continuous Isoprene Measurements in a UK Temperate Forest for a Whole Growing Season: Effects of Drought Stress During the 2018 Heatwave, *Geophys. Res. Lett.*, 47, e2020GL088885, <https://doi.org/10.1029/2020GL088885>, 2020.
- 1150 Feser, F., Van Garderen, L., and Hansen, F.: The Summer Heatwave 2022 over Western Europe: An Attribution to Anthropogenic Climate Change, *Bull. Am. Meteorol. Soc.*, 105, E2175–E2179, <https://doi.org/10.1175/BAMS-D-24-0017.1>, 2024.
- Finlayson-Pitts, B. J. and Pitts, J. N.: Tropospheric Air Pollution: Ozone, Airborne Toxics, Polycyclic Aromatic Hydrocarbons, and Particles, *Science*, 276, 1045–1051, <https://doi.org/10.1126/science.276.5315.1045>, 1997.
- 1155 Fischer, E. M. and Schär, C.: Consistent geographical patterns of changes in high-impact European heatwaves, *Nat. Geosci.*, 3, 398–403, <https://doi.org/10.1038/ngeo866>, 2010.
- Fu, W., Zhao, T., Sun, X., Bai, Y., Yang, Q., Shen, L., Liang, D., Tan, C., Luo, Y., and Yang, K.: Recent-year variations in O₃ pollution with high-temperature suppression over central China, *Environ. Pollut.*, 349, 123932, 2024.



- 1160 Garg, A., Desservettaz, M., Christodoulou, A., Christoudias, T., Kanawade, V. P., Savvides, C., Vrekoussis, M., Naqui, S., Jokinen, T., Byron, J., Williams, J., Mihalopoulos, N., Liakakou, E., Sciare, J., and Bourtsoukidis, E.: Heat and continental transport shape the variability of volatile organic compounds in the Eastern Mediterranean: insights from multi-year observations and regional modeling, *Atmos. Chem. Phys.*, 26, 2597–2622, <https://doi.org/10.5194/acp-26-2597-2026>, 2026.
- 1165 Gaston, C. J., Riedel, T. P., Zhang, Z., Gold, A., Surratt, J. D., and Thornton, J. A.: Reactive Uptake of an Isoprene-Derived Epoxydiol to Submicron Aerosol Particles, *Environ. Sci. Technol.*, 48, 11178–11186, <https://doi.org/10.1021/es5034266>, 2014.
- Geron, C. D., Guenther, A. B., and Pierce, T. E.: An improved model for estimating emissions of volatile organic compounds from forests in the eastern United States, *J. Geophys. Res. Atmos.*, 99, 12773–12791, <https://doi.org/https://doi.org/10.1029/94JD00246>, 1994.
- 1170 Gil, J., Lee, M., Park, M., Kim, C.-H., Koo, J., Lee, H., Kang, S., and Rhee, H.: Accelerated O₃ formation triggered by summer heatwaves in megacity Seoul, *Environ. Sci. Process. Impacts*, 28, 752–762, <https://doi.org/10.1039/D5EM00629E>, 2026.
- 1175 Gkatzelis, G. I., Coggon, M. M., McDonald, B. C., Peischl, J., Gilman, J. B., Aikin, K. C., Robinson, M. A., Canonaco, F., Prevot, A. S. H., Trainer, M., and Warneke, C.: Observations Confirm that Volatile Chemical Products Are a Major Source of Petrochemical Emissions in U.S. Cities, *Environ. Sci. Technol.*, 55, 4332–4343, <https://doi.org/10.1021/acs.est.0c05471>, 2021.
- Gu, Y., Liu, B., Meng, H., Song, S., Dai, Q., Shi, L., Feng, Y., and Hopke, P. K.: Source apportionment of consumed volatile organic compounds in the atmosphere, *J. Hazard. Mater.*, 459, 132138, <https://doi.org/https://doi.org/10.1016/j.jhazmat.2023.132138>, 2023.
- 1180 Gu, Y., Liu, B., Ma, S., Luo, Z., Zhang, J., Liang, D., Li, Y., Zhang, Y., and Feng, Y.: Novel quantitative method of reactive losses of ambient VOCs coupling chemical transport model simulation with receptor measurement, *J. Hazard. Mater.*, 496, 139165, <https://doi.org/https://doi.org/10.1016/j.jhazmat.2025.139165>, 2025.
- 1185 Guenther, A., Hewitt, C. N., Erickson, D., Fall, R., Geron, C., Graedel, T., Harley, P., Klinger, L., Lerdau, M., McKay, W. A., Pierce, T., Scholes, B., Steinbrecher, R., Tallamraju, R., Taylor, J., and Zimmerman, P.: A global model of natural volatile organic compound emissions, *J. Geophys. Res. Atmos.*, 100, 8873–8892, <https://doi.org/https://doi.org/10.1029/94JD02950>, 1995.
- Guenther, A., Karl, T., Harley, P., Wiedinmyer, C., Palmer, P. I., and Geron, C.: Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature), *Atmos. Chem. Phys.*, 6, 3181–3210, <https://doi.org/10.5194/acp-6-3181-2006>, 2006.
- 1190 Guenther, A. B., Zimmerman, P. R., Harley, P. C., Monson, R. K., and Fall, R.: Isoprene and monoterpene emission rate variability: Model evaluations and sensitivity analyses, *J. Geophys. Res. Atmos.*, 98, 12609–12617, <https://doi.org/https://doi.org/10.1029/93JD00527>, 1993.
- Guenther, A. B., Jiang, X., Heald, C. L., Sakulyanontvittaya, T., Duhl, T., Emmons, L. K., and Wang, X.: The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1): an extended and updated framework for modeling biogenic emissions, *Geosci. Model Dev.*, 5, 1471–1492, <https://doi.org/10.5194/gmd-5-1471-2012>, 2012.



- 1195 Guo, Y., Chen, P., Xie, Y., Wang, Y., Mu, Y., Zhou, R., Niu, Y., Shi, X., Zhu, J., Liang, J., and Liu, Q.: Association of Daytime-Only, Nighttime-Only, and Compound Heat Waves With Preterm Birth by Urban-Rural Area and Regional Socioeconomic Status in China, *JAMA Netw. Open*, 6, e2326987, <https://doi.org/10.1001/jamanetworkopen.2023.26987>, 2023.
- 1200 Hakola, H., Tarvainen, V., Praplan, A. P., Jaars, K., Hemmilä, M., Kulmala, M., Bäck, J., and Hellén, H.: Terpenoid and carbonyl emissions from Norway spruce in Finland during the growing season, *Atmos. Chem. Phys.*, 17, 3357–3370, <https://doi.org/10.5194/acp-17-3357-2017>, 2017.
- Han, Q., Sun, S., Liu, Z., Xu, W., and Shi, P.: Accelerated exacerbation of global extreme heatwaves under warming scenarios, *Int. J. Climatol.*, 42, 5430–5441, <https://doi.org/10.1002/joc.7541>, 2022.
- 1205 Hao, Y., Li, P., Gou, Y., Wang, Z., Tian, M., Chen, Y., Kuang, Y., Xu, H., Wan, F., Luo, Y., Huang, W., and Chen, J.: Divergent changes in aerosol optical hygroscopicity and new particle formation during a heatwave of summer 2022, *Atmos. Chem. Phys.*, 25, 12811–12830, <https://doi.org/10.5194/acp-25-12811-2025>, 2025.
- Hao, Z., Hao, F., Xia, Y., Feng, S., Sun, C., Zhang, X., Fu, Y., Hao, Y., Zhang, Y., and Meng, Y.: Compound droughts and hot extremes: Characteristics, drivers, changes, and impacts, *Earth-Sci. Rev.*, 235, 104241, <https://doi.org/10.1016/j.earscirev.2022.104241>, 2022.
- 1210 Hass-Mitchell, T., Joo, T., Rogers, M., Nault, B. A., Soong, C., Tran, M., Seo, M., Machesky, J. E., Canagaratna, M., Roscioli, J., Clafflin, M. S., Lerner, B. M., Blomdahl, D. C., Misztal, P. K., Ng, N. L., Dillner, A. M., Bahreini, R., Russell, A., Krechmer, J. E., Lambe, A., and Gentner, D. R.: Increasing Contributions of Temperature-Dependent Oxygenated Organic Aerosol to Summertime Particulate Matter in New York City, *ACS EST Air*, 1, 113–128, <https://doi.org/10.1021/acsestair.3c00037>, 2024.
- 1215 Hirsch, A. L., Evans, J. P., Di Virgilio, G., Perkins-Kirkpatrick, S. E., Argüeso, D., Pitman, A. J., Carouge, C. C., Kala, J., Andrys, J., Petrelli, P., and Rockel, B.: Amplification of Australian Heatwaves via Local Land-Atmosphere Coupling, *J. Geophys. Res. Atmos.*, 124, 13625–13647, <https://doi.org/10.1029/2019JD030665>, 2019.
- Hopke, P. K.: Review of receptor modeling methods for source apportionment, *J. Air Waste Manag. Assoc.*, 66, 237–259, <https://doi.org/10.1080/10962247.2016.1140693>, 2016.
- 1220 Horne, J. R. and Dabdub, D.: Impact of global climate change on ozone, particulate matter, and secondary organic aerosol concentrations in California: A model perturbation analysis, *Atmos. Environ.*, 153, 1–17, <https://doi.org/https://doi.org/10.1016/j.atmosenv.2016.12.049>, 2017.
- Hu, J., Chen, Z., Qin, X., and Dong, P.: Reversible and irreversible gas–particle partitioning of dicarbonyl compounds observed in the real atmosphere, *Atmos. Chem. Phys.*, 22, 6971–6987, <https://doi.org/10.5194/acp-22-6971-2022>, 2022.
- 1225 Huang, J., Yuan, Z., Duan, Y., Liu, D., Fu, Q., Liang, G., Li, F., and Huang, X.: Quantification of temperature dependence of vehicle evaporative volatile organic compound emissions from different fuel types in China, *Sci. Total Environ.*, 813, 152661, <https://doi.org/https://doi.org/10.1016/j.scitotenv.2021.152661>, 2022.
- 1230 Huang, M., Feng, Z., and Liao, T.: Shift of surface O₃-NO_x-VOC sensitivity with temperature in the Guangdong-Hong Kong-Macao Greater Bay Area, South China, *Environ. Pollut.*, 372, 125974,



- <https://doi.org/https://doi.org/10.1016/j.envpol.2025.125974>, 2025.
- Huang, S., Xiong, J., and Zhang, Y.: Impact of Temperature on the Ratio of Initial Emittable Concentration to Total Concentration for Formaldehyde in Building Materials: Theoretical Correlation and Validation, *Environ. Sci. Technol.*, 49, 1537–1544, <https://doi.org/10.1021/es5051875>, 2015.
- 1235 Hulley, G. C., Dousset, B., and Kahn, B. H.: Rising Trends in Heatwave Metrics Across Southern California, *Earths Future*, 8, e2020EF001480, <https://doi.org/10.1029/2020EF001480>, 2020.
- India Meteorological Department (IMD): Standard Operation Procedure – Weather Forecasting and Warning Services, India Meteorological Department, https://mausam.imd.gov.in/imd_latest/contents/pdf/forecasting_sop.pdf (last access: 14 September 2026), 2021.
- 1240 Intergovernmental Panel On Climate Change (Ipcc): Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1st ed., Cambridge University Press, <https://doi.org/10.1017/9781009157896>, 2023a.
- Intergovernmental Panel On Climate Change (Ipcc): Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1st ed., Cambridge University Press, <https://doi.org/10.1017/9781009325844>, 2023b.
- 1245 Janyasuthiwong, S., Choomanee, P., Bualert, S., Maneejantra, S., Charoenpun, T., Chommon, W., and Jitjun, S.: Biogenic volatile organic compound emission from tropical plants in relation to temperature changes, *Environ. Chall.*, 9, 100643, <https://doi.org/10.1016/j.envc.2022.100643>, 2022.
- Jiang, J., Liu, Y., Meng, J., Wu, G., He, B., Ma, T., Bao, W., and Fan, J.: Dry soil moisture on the Tibetan plateau drives synchronous extreme heatwaves in Europe and East Asia, *Npj Clim. Atmos. Sci.*, 7, 281, <https://doi.org/10.1038/s41612-024-00831-x>, 2024.
- 1250 Jiang, Z., McDonald, B. C., Worden, H., Worden, J. R., Miyazaki, K., Qu, Z., Henze, D. K., Jones, D. B. A., Arellano, A. F., Fischer, E. V., Zhu, L., and Boersma, K. F.: Unexpected slowdown of US pollutant emission reduction in the past decade, *Proc. Natl. Acad. Sci.*, 115, 5099–5104, <https://doi.org/10.1073/pnas.1801191115>, 2018.
- 1255 Kaiser, J., Jacob, D. J., Zhu, L., Travis, K. R., Fisher, J. A., González Abad, G., Zhang, L., Zhang, X., Fried, A., Crounse, J. D., St. Clair, J. M., and Wisthaler, A.: High-resolution inversion of OMI formaldehyde columns to quantify isoprene emission on ecosystem-relevant scales: application to the southeast US, *Atmos. Chem. Phys.*, 18, 5483–5497, <https://doi.org/10.5194/acp-18-5483-2018>, 2018.
- Kanti, F. S., Alari, A., Chaix, B., and Benmarhnia, T.: Comparison of various heat waves definitions and the burden of heat-related mortality in France: Implications for existing early warning systems, *Environ. Res.*, 215, 114359, <https://doi.org/10.1016/j.envres.2022.114359>, 2022.
- 1260 Kaspar, F., Andersson, A., Ziese, M., and Hollmann, R.: Contributions to the Improvement of Climate Data Availability and Quality for Sub-Saharan Africa, *Front. Clim.*, 3, 815043, <https://doi.org/10.3389/fclim.2021.815043>, 2022.
- 1265 Kiland, K. J., Marroquin, K. L., Smith, N. R., Xu, S., Nizkorodov, S. A., and Bertram, A. K.: A new hot-stage



- microscopy technique for measuring temperature-dependent viscosities of aerosol particles and its application to farnesene secondary organic aerosol, *Atmos. Meas. Tech.*, 15, 5545–5561, <https://doi.org/10.5194/amt-15-5545-2022>, 2022.
- 1270 Kim, D., Cho, C., Jeong, S., Lee, S., Nault, B. A., Campuzano-Jost, P., Day, D. A., Schroder, J. C., Jimenez, J. L., Volkamer, R., Blake, D. R., Wisthaler, A., Fried, A., DiGangi, J. P., Diskin, G. S., Pusede, S. E., Hall, S. R., Ullmann, K., Huey, L. G., Tanner, D. J., Dibb, J., Knote, C. J., and Min, K.-E.: Field observational constraints on the controllers in glyoxal (CHOCHO) reactive uptake to aerosol, *Atmos. Chem. Phys.*, 22, 805–821, <https://doi.org/10.5194/acp-22-805-2022>, 2022.
- 1275 Kleinman, L. I.: Low and high NO_x tropospheric photochemistry, *J. Geophys. Res. Atmos.*, 99, 16831–16838, <https://doi.org/10.1029/94JD01028>, 1994.
- Kleist, E., Mentel, T. F., Andres, S., Bohné, A., Folkers, A., Kiendler-Scharr, A., Rudich, Y., Springer, M., Tillmann, R., and Wildt, J.: Irreversible impacts of heat on the emissions of monoterpenes, sesquiterpenes, phenolic BVOC and green leaf volatiles from several tree species, *Biogeosciences*, 9, 5111–5123, <https://doi.org/10.5194/bg-9-5111-2012>, 2012.
- 1280 Komenda, M. and Koppmann, R.: Monoterpene emissions from Scots pine (*Pinus sylvestris*): Field studies of emission rate variabilities, *J. Geophys. Res. Atmos.*, 107, ACH 1-1-ACH 1-13, <https://doi.org/10.1029/2001JD000691>, 2002.
- Kong, X., Kong, L., Chen, D., Liu, S., Feng, M., Tan, Q., Zhou, L., and Yang, F.: The Impact of Extreme Summer Heat on VOC Sensitivity and Ozone Formation: Insights From Field Campaigns in a Sichuan Basin Megacity, China, *J. Geophys. Res. Atmos.*, 130, e2024JD042945, <https://doi.org/10.1029/2024JD042945>, 2025.
- 1285 Korea Meteorological Administration (KMA): Issuance Criteria for Weather Advisories and Warnings, Korea Meteorological Administration, <https://www.kma.go.kr/neng/forecast/warning.do> (last access: 14 September 2026), 2026.
- 1290 Kroll, J. H. and Seinfeld, J. H.: Chemistry of secondary organic aerosol: Formation and evolution of low-volatility organics in the atmosphere, *Atmos. Environ.*, 42, 3593–3624, <https://doi.org/10.1016/j.atmosenv.2008.01.003>, 2008.
- Lakshmi, S., Saraswathi, S., Pai, D. S., and Agnihotri, G.: Decadal Evolution and Multi-Scale Climate Teleconnections of Heatwaves Over Tamil Nadu, India (1981–2020): Trends, Spatial Expansion and Atmospheric Drivers, *Int. J. Climatol.*, 46, e70205, <https://doi.org/10.1002/joc.70205>, 2026.
- 1295 Lannuque, V., D’Anna, B., Kostenidou, E., Couvidat, F., Martinez-Valiente, A., Eichler, P., Wisthaler, A., Müller, M., Temime-Roussel, B., Valorso, R., and Sartelet, K.: Gas–particle partitioning of toluene oxidation products: an experimental and modeling study, *Atmos. Chem. Phys.*, 23, 15537–15560, <https://doi.org/10.5194/acp-23-15537-2023>, 2023.
- 1300 Lee, J. D., Lewis, A. C., Monks, P. S., Jacob, M., Hamilton, J. F., Hopkins, J. R., Watson, N. M., Saxton, J. E., Ennis, C., Carpenter, L. J., Carslaw, N., Fleming, Z., Bandy, B. J., Oram, D. E., Penkett, S. A., Slemr, J., Norton, E., Rickard, A. R., Whalley, L. K., Heard, D. E., Bloss, W. J., Gravestock, T., Smith, S. C., Stanton, J., Pilling, M. J., and Jenkin, M. E.: Ozone photochemistry and elevated isoprene during the UK heatwave of august 2003, *Atmos. Environ.*, 40,



- 7598–7613, <https://doi.org/https://doi.org/10.1016/j.atmosenv.2006.06.057>, 2006.
- 1305 Lhotka, O. and Kysely, J.: The 2021 European Heat Wave in the Context of Past Major Heat Waves, *Earth Space Sci.*, 9, e2022EA002567, <https://doi.org/10.1029/2022EA002567>, 2022.
- Li, H., Ciais, P., Kumar, P., Hauglustaine, D. A., Chevallier, F., Broquet, G., Millet, D. B., Wells, K. C., Lian, J., and Zheng, B.: Global biogenic isoprene emissions 2013–2020 inferred from satellite isoprene observations, *Earth Syst. Sci. Data*, 17, 7035–7054, <https://doi.org/10.5194/essd-17-7035-2025>, 2025a.
- 1310 Li, H., Ciais, P., Kumar, P., Broquet, G., Chevallier, F., Hauglustaine, D. A., Millet, D. B., Wells, K. C., Lian, J., Bourtsoukidis, E., Zhang, K., and Zheng, B.: Contrasting Biogenic Isoprene Emission Responses to La Niña and El Niño Driven by Temperature: Insights from HCHO-Based Global Inversion, *Environ. Sci. Technol.*, 60, 3403–3415, <https://doi.org/10.1021/acs.est.5c12927>, 2026.
- Li, J. and Knopf, D. A.: Representation of Multiphase OH Oxidation of Amorphous Organic Aerosol for Tropospheric Conditions, *Environ. Sci. Technol.*, 55, 7266–7275, <https://doi.org/10.1021/acs.est.0c07668>, 2021.
- 1315 Li, K. and Amatus, G.: Spatiotemporal changes of heat waves and extreme temperatures in the main cities of China from 1955 to 2014, *Nat. Hazards Earth Syst. Sci.*, 20, 1889–1901, <https://doi.org/10.5194/nhess-20-1889-2020>, 2020.
- Li, K., Jacob, D. J., Liao, H., Zhu, J., Shah, V., Shen, L., Bates, K. H., Zhang, Q., and Zhai, S.: A two-pollutant strategy for improving ozone and particulate air quality in China, *Nat. Geosci.*, 12, 906–910, <https://doi.org/10.1038/s41561-019-0464-x>, 2019.
- 1320 Li, M., Huang, X., Yan, D., Lai, S., Zhang, Z., Zhu, L., Lu, Y., Jiang, X., Wang, N., Wang, T., Song, Y., and Ding, A.: Coping with the concurrent heatwaves and ozone extremes in China under a warming climate, *Sci. Bull.*, 69, 2938–2947, <https://doi.org/https://doi.org/10.1016/j.scib.2024.05.034>, 2024.
- Li, S., Wang, H., and Lu, X.: Anthropogenic emission controls reduce summertime ozone–temperature sensitivity in the United States, *Atmos. Chem. Phys.*, 25, 2725–2743, <https://doi.org/10.5194/acp-25-2725-2025>, 2025b.
- 1325 Li, S., Yuan, X., Li, S., Zhou, Y., Wang, S., Zhang, K., Agathokleous, E., Blande, J. D., and Feng, Z.: Extreme Heat Event Alters BVOC Responses to Elevated Ozone: From Physiology to Emission Patterns, *Environ. Sci. Technol.*, 59, 12132–12144, <https://doi.org/10.1021/acs.est.5c01132>, 2025c.
- Li, X., Yao, Z., Wang, X., Yu, C., Che, S., Gong, Z., Feng, G., and Li, T.: Possible Causes of Extremely Warm Early Summer in North China During Cold and Warm Periods, *Front. Clim.*, 3, 762997, <https://doi.org/10.3389/fclim.2021.762997>, 2021.
- 1330 Li, Y. and Shiraiwa, M.: Timescales of secondary organic aerosols to reach equilibrium at various temperatures and relative humidities, *Atmos. Chem. Phys.*, 19, 5959–5971, <https://doi.org/10.5194/acp-19-5959-2019>, 2019.
- Li, Z., Ratliff, E. A., and Sharkey, T. D.: Effect of Temperature on Postillumination Isoprene Emission in Oak and Poplar, *Plant Physiol.*, 155, 1037–1046, <https://doi.org/10.1104/pp.110.167551>, 2011.
- 1335 Lin, L., Gao, T., Luo, M., Ge, E., Yang, Y., Liu, Z., Zhao, Y., and Ning, G.: Contribution of urbanization to the changes in extreme climate events in urban agglomerations across China, *Sci. Total Environ.*, 744, 140264,



<https://doi.org/10.1016/j.scitotenv.2020.140264>, 2020.

1340 Lin, W., Zhao, Z., Lai, J., Liu, Y., Huang, X., and Yi, Z.: Effects of temperature and light on isoprene and monoterpene emission from *Loropetalum chinense* and *Nandina domestica*, *Acta Sci. Circumstantiae*, 39, 3126–3133, <https://doi.org/10.13671/j.hjkxxb.2019.0135>, 2019.

Lindwall, F., Schollert, M., Michelsen, A., Blok, D., and Rinnan, R.: Fourfold higher tundra volatile emissions due to arctic summer warming, *J. Geophys. Res. Biogeosciences*, 121, 895–902, <https://doi.org/https://doi.org/10.1002/2015JG003295>, 2016.

1345 Liu, B., Yang, Y., Yang, T., Dai, Q., Zhang, Y., Feng, Y., and Hopke, P. K.: Effect of photochemical losses of ambient volatile organic compounds on their source apportionment, *Environ. Int.*, 172, 107766, <https://doi.org/https://doi.org/10.1016/j.envint.2023.107766>, 2023.

Liu, B., Gu, Y., Wu, Y., Dai, Q., Song, S., Feng, Y., and Hopke, P. K.: Review of source analyses of ambient volatile organic compounds considering reactive losses: methods of reducing loss effects, impacts of losses, and sources, *Atmos. Chem. Phys.*, 24, 12861–12879, <https://doi.org/10.5194/acp-24-12861-2024>, 2024.

1350 Liu, C., Zhao, M., Tan, S., Chen, C., Qiao, J., and Shi, K.: Surface ozone suppression by high temperature-induced ozone chemistry regime, *Atmos. Pollut. Res.*, 17, 102824, <https://doi.org/https://doi.org/10.1016/j.apr.2025.102824>, 2026a.

Liu, J. and Li, M.: Characteristics and Driving Mechanisms of Heatwaves in China During July and August, *Atmosphere*, 16, 434, <https://doi.org/10.3390/atmos16040434>, 2025.

1355 Liu, S. and Jaffe, D. A.: Surface Atmospheric Formaldehyde Trends in the U.S. Driven by Temperature-Dependent Biogenic Precursor Emissions and Influenced by Wildfires, *ACS EST Air*, 3, 1167–1175, <https://doi.org/10.1021/acsestair.6c00010>, 2026.

1360 Liu, X., Wang, M., An, T., Zhang, X., Wang, T., Lara, R., Monge, M., Dufresne, M., Yañez-Serrano, A. M., Seco, R., Gohy, M., Petit, P., Chevalier, A., Vagnot, M.-P., Fortier, Y., Baudic, A., Gherzi, V., Gille, G., Lanzi, L., Gros, V., Petit, J.-E., Simon, L., Hellén, H., Reimann, S., Le Bras, Z., Müller, M. J., Beddows, D., Hou, S., Shi, Z., Harrison, R. M., Bloss, W., Dernie, J., Sauvage, S., Lewis, A., Hopkins, J., Duan, X., Hopke, P. K., Alastuey, A., Querol, X., and Salameh, T.: Analysis of the abundance and impacts of volatile organic compounds across Europe, *Npj Clim. Atmos. Sci.*, 9, 103, <https://doi.org/10.1038/s41612-026-01378-9>, 2026b.

1365 Lu, J., Gao, Y., Huang, D., Jing, S., Wang, H., Li, Y., Ding, X., Hu, Q., Xiu, G., Lin, M., Zhang, W., and Huang, C.: Reactive Organic Gases from Vehicle Evaporative Emissions: Rates, Compositions, and Temperature Effects, *Environ. Sci. Technol.*, 59, 11132–11144, <https://doi.org/10.1021/acs.est.4c09415>, 2025.

Ma, F., Yuan, X., Jiao, Y., and Ji, P.: Unprecedented Europe Heat in June–July 2019: Risk in the Historical and Future Context, *Geophys. Res. Lett.*, 47, e2020GL087809, <https://doi.org/10.1029/2020GL087809>, 2020.

1370 Ma, X., Tan, Z., Lu, K., Yang, X., Chen, X., Wang, H., Chen, S., Fang, X., Li, S., Li, X., Liu, J., Liu, Y., Lou, S., Qiu, W., Wang, H., Zeng, L., and Zhang, Y.: OH and HO₂ radical chemistry at a suburban site during the EXPLORE-YRD campaign in 2018, *Atmos. Chem. Phys.*, 22, 7005–7028, <https://doi.org/10.5194/acp-22-7005-2022>, 2022.



- 1375 Marengo, J. A., Costa, M. C., Cunha, A. P., Espinoza, J., Jimenez, J. C., Libonati, R., Geirinhas, J. L., Miranda, V., Trigo, I. F., Sierra, J. P., Maia, T. O., and Medeiros, O.: Characterisation of the Exceptional Heatwave Conditions Observed in Brazil During the Record-Hot Years of 2024 and 2025, *Int. J. Climatol.*, 46, e70219, <https://doi.org/10.1002/joc.70219>, 2026.
- Martinez-Villalobos, C., Fu, D., Loikith, P., and Neelin, J. D.: Accelerating increases in heat waves durations under global warming, <https://doi.org/10.21203/rs.3.rs-4999972/v1>, 9 October 2024., 2024.
- Marx, W., Haunschild, R., and Bornmann, L.: Heat waves: a hot topic in climate change research, *Theor. Appl. Climatol.*, 146, 781–800, <https://doi.org/10.1007/s00704-021-03758-y>, 2021.
- 1380 Mayer, A. and Wirth, V.: Two different perspectives on heatwaves within the Lagrangian framework, *Weather Clim. Dyn.*, 6, 131–150, <https://doi.org/10.5194/wcd-6-131-2025>, 2025.
- McDonald, B. C., Gouw, J. A. de, Gilman, J. B., Jathar, S. H., Akherati, A., Cappa, C. D., Jimenez, J. L., Lee-Taylor, J., Hayes, P. L., McKeen, S. A., Cui, Y. Y., Kim, S.-W., Gentner, D. R., Isaacman-VanWertz, G., Goldstein, A. H., Harley, R. A., Frost, G. J., Roberts, J. M., Ryerson, T. B., and Trainer, M.: Volatile chemical products emerging as largest petrochemical source of urban organic emissions, *Science*, 359, 760–764, <https://doi.org/10.1126/science.aag0524>, 2018.
- 1385 McGregor, G. R., Bessemoulin, P., Ebi, K. L., and Menne, B. (Eds.): Heatwaves and health: guidance on warning-system development, World Meteorological Organization : World Health Organization, Geneva, 2015
- 1390 McNeill, V. F.: Aqueous Organic Chemistry in the Atmosphere: Sources and Chemical Processing of Organic Aerosols, *Environ. Sci. Technol.*, 49, 1237–1244, <https://doi.org/10.1021/es5043707>, 2015.
- Meng, X., Jiang, J., Chen, T., Zhang, Z., Lu, B., Liu, C., Xue, L., Chen, J., Herrmann, H., and Li, X.: Chemical drivers of ozone change in extreme temperatures in eastern China, *Sci. Total Environ.*, 874, 162424, <https://doi.org/https://doi.org/10.1016/j.scitotenv.2023.162424>, 2023.
- 1395 Millet, D. B., Jacob, D. J., Boersma, K. F., Fu, T.-M., Kurosu, T. P., Chance, K., Heald, C. L., and Guenther, A.: Spatial distribution of isoprene emissions from North America derived from formaldehyde column measurements by the OMI satellite sensor, *J. Geophys. Res. Atmos.*, 113, <https://doi.org/https://doi.org/10.1029/2007JD008950>, 2008.
- Miralles, D. G., Gentine, P., Seneviratne, S. I., and Teuling, A. J.: Land–atmospheric feedbacks during droughts and heatwaves: state of the science and current challenges, *Ann. N. Y. Acad. Sci.*, 1436, 19–35, <https://doi.org/10.1111/nyas.13912>, 2019.
- 1400 Mo, Z., Cui, R., Yuan, B., Cai, H., McDonald, B. C., Li, M., Zheng, J., and Shao, M.: A mass-balance-based emission inventory of non-methane volatile organic compounds (NMVOCs) for solvent use in China, *Atmos. Chem. Phys.*, 21, 13655–13666, <https://doi.org/10.5194/acp-21-13655-2021>, 2021.
- 1405 Monks, P. S., Granier, C., Fuzzi, S., Stohl, A., Williams, M. L., Akimoto, H., Amann, M., Baklanov, A., Baltensperger, U., Bey, I., Blake, N., Blake, R. S., Carslaw, K., Cooper, O. R., Dentener, F., Fowler, D., Fragkou, E., Frost, G. J., Generoso, S., Ginoux, P., Grewe, V., Guenther, A., Hansson, H. C., Henne, S., Hjorth, J., Hofzumahaus, A., Huntrieser, H., Isaksen, I. S. A., Jenkin, M. E., Kaiser, J., Kanakidou, M., Klimont, Z., Kulmala, M., Laj, P., Lawrence, M. G., Lee, J. D., Liousse, C., Maione, M., McFiggans, G., Metzger, A., Mieville, A., Moussiopoulos, N., Orlando, J. J.,



- 1410 O'Dowd, C. D., Palmer, P. I., Parrish, D. D., Petzold, A., Platt, U., Pöschl, U., Prévôt, A. S. H., Reeves, C. E., Reimann, S., Rudich, Y., Sellegri, K., Steinbrecher, R., Simpson, D., Brink, H. ten, Theloke, J., Werf, G. R. van der, Vautard, R., Vestreng, V., Vlachokostas, C., and Glasow, R. von: Atmospheric composition change – global and regional air quality, *Atmos. Environ.*, 43, 5268–5350, <https://doi.org/https://doi.org/10.1016/j.atmosenv.2009.08.021>, 2009.
- 1415 Monks, P. S., Archibald, A. T., Colette, A., Cooper, O., Coyle, M., Derwent, R., Fowler, D., Granier, C., Law, K. S., Mills, G. E., Stevenson, D. S., Tarasova, O., Thouret, V., von Schneidemesser, E., Sommariva, R., Wild, O., and Williams, M. L.: Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer, *Atmos. Chem. Phys.*, 15, 8889–8973, <https://doi.org/10.5194/acp-15-8889-2015>, 2015.
- Morino, Y., Sadanaga, Y., Sato, K., Sakamoto, Y., Muraoka, T., Miyatake, K., Li, J., and Kajii, Y.: Direct evaluation of the ozone production regime in smog chamber experiments, *Atmos. Environ.*, 309, 119889, <https://doi.org/https://doi.org/10.1016/j.atmosenv.2023.119889>, 2023.
- 1420 Nagalingam, S., Seco, R., Kim, S., and Guenther, A.: Heat stress strongly induces monoterpene emissions in some plants with specialized terpenoid storage structures, *Agric. For. Meteorol.*, 333, 109400, <https://doi.org/https://doi.org/10.1016/j.agrformet.2023.109400>, 2023.
- Nagalingam, S., Wang, H., Kim, S., and Guenther, A.: Unexpectedly strong heat stress induction of monoterpene, methylbutenol, and other volatile emissions for conifers in the cypress family (Cupressaceae), *Sci. Total Environ.*, 956, 177336, <https://doi.org/https://doi.org/10.1016/j.scitotenv.2024.177336>, 2024.
- 1425 Nairn, J., Moise, A., and Ostendorf, B.: The impact of humidity on Australia's operational heatwave services, *Clim. Serv.*, 27, 100315, <https://doi.org/10.1016/j.cliser.2022.100315>, 2022.
- Nie, W., Yan, C., Huang, D. D., Wang, Z., Liu, Y., Qiao, X., Guo, Y., Tian, L., Zheng, P., Xu, Z., Li, Y., Xu, Z., Qi, X., Sun, P., Wang, J., Zheng, F., Li, X., Yin, R., Dallenbach, K. R., Bianchi, F., Petäjä, T., Zhang, Y., Wang, M., Schervish, M., Wang, S., Qiao, L., Wang, Q., Zhou, M., Wang, H., Yu, C., Yao, D., Guo, H., Ye, P., Lee, S., Li, Y. J., Liu, Y., Chi, X., Kerminen, V.-M., Ehn, M., Donahue, N. M., Wang, T., Huang, C., Kulmala, M., Worsnop, D., Jiang, J., and Ding, A.: Secondary organic aerosol formed by condensing anthropogenic vapours over China's megacities, *Nat. Geosci.*, 15, 255–261, <https://doi.org/10.1038/s41561-022-00922-5>, 2022.
- 1430 Nie, W., Yan, C., Yang, L., Roldin, P., Liu, Y., Vogel, A. L., Molteni, U., Stolzenburg, D., Finkenzeller, H., Amorim, A., Bianchi, F., Curtius, J., Dada, L., Draper, D. C., Duplissy, J., Hansel, A., He, X.-C., Hofbauer, V., Jokinen, T., Kim, C., Lehtipalo, K., Nichman, L., Mauldin, R. L., Makhmutov, V., Mentler, B., Mizelli-Ojdanic, A., Petäjä, T., Quéléver, L. L. J., Schallhart, S., Simon, M., Tauber, C., Tomé, A., Volkamer, R., Wagner, A. C., Wagner, R., Wang, M., Ye, P., Li, H., Huang, W., Qi, X., Lou, S., Liu, T., Chi, X., Dommen, J., Baltensperger, U., El Haddad, I., Kirkby, J., Worsnop, D., Kulmala, M., Donahue, N. M., Ehn, M., and Ding, A.: NO at low concentration can enhance the formation of highly oxygenated biogenic molecules in the atmosphere, *Nat. Commun.*, 14, 3347, <https://doi.org/10.1038/s41467-023-39066-4>, 2023.
- 1440 Niu, Z., Kong, S., Zheng, H., Yan, Q., Liu, J., Feng, Y., Wu, J., Zheng, S., Zeng, X., Yao, L., Zhang, Y., Fan, Z., Cheng, Y., Liu, X., Wu, F., Qin, S., Yan, Y., Ding, F., Liu, W., Zhu, K., Liu, D., and Qi, S.: Temperature dependence of source profiles for volatile organic compounds from typical volatile emission sources, *Sci. Total Environ.*, 751, 141741, <https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.141741>, 2021.
- 1445



- Odum, J. R., Hoffmann, T., Bowman, F., Collins, D., Flagan, R. C., and Seinfeld, J. H.: Gas/Particle Partitioning and Secondary Organic Aerosol Yields, *Environ. Sci. Technol.*, 30, 2580–2585, <https://doi.org/10.1021/es950943+>, 1996.
- Oliver, E. C. J., Donat, M. G., Burrows, M. T., Moore, P. J., Smale, D. A., Alexander, L. V., Benthuyssen, J. A., Feng, M., Sen Gupta, A., Hobday, A. J., Holbrook, N. J., Perkins-Kirkpatrick, S. E., Scannell, H. A., Straub, S. C., and Wernberg, T.: Longer and more frequent marine heatwaves over the past century, *Nat. Commun.*, 9, 1324, <https://doi.org/10.1038/s41467-018-03732-9>, 2018.
- Oomen, G.-M., Müller, J.-F., Stavrakou, T., De Smedt, I., Blumenstock, T., Kivi, R., Makarova, M., Palm, M., Röhling, A., Té, Y., Vigouroux, C., Friedrich, M. M., Frieß, U., Hendrick, F., Merlaud, A., PETERS, A., Richter, A., Van Roozendaal, M., and Wagner, T.: Weekly derived top-down volatile-organic-compound fluxes over Europe from TROPOMI HCHO data from 2018 to 2021, *Atmos. Chem. Phys.*, 24, 449–474, <https://doi.org/10.5194/acp-24-449-2024>, 2024.
- Oswald, E. M.: An Analysis of the Prevalence of Heat Waves in the United States between 1948 and 2015, *J. Appl. Meteorol. Climatol.*, 57, 1535–1549, <https://doi.org/10.1175/JAMC-D-17-0274.1>, 2018.
- Paatero, P. and Tapper, U.: Positive matrix factorization: A non-negative factor model with optimal utilization of error estimates of data values, *Environmetrics*, 5, 111–126, <https://doi.org/https://doi.org/10.1002/env.3170050203>, 1994.
- Palmer, P. I., Abbot, D. S., Fu, T.-M., Jacob, D. J., Chance, K., Kurosui, T. P., Guenther, A., Wiedinmyer, C., Stanton, J. C., Pilling, M. J., Pressley, S. N., Lamb, B., and Sumner, A. L.: Quantifying the seasonal and interannual variability of North American isoprene emissions using satellite observations of the formaldehyde column, *J. Geophys. Res. Atmos.*, 111, <https://doi.org/https://doi.org/10.1029/2005JD006689>, 2006.
- Pan, J., Huang, Z., Ouyang, H., and Wang, X.: Contrasting Mechanisms of Heatwave-Ozone Pollution Compound Events and Independent Heatwave Events in the Yangtze River Delta, *J. Geophys. Res. Atmos.*, 131, e2025JD045802, <https://doi.org/https://doi.org/10.1029/2025JD045802>, 2026.
- Pankow, J. F.: An absorption model of gas/particle partitioning of organic compounds in the atmosphere, *Atmos. Environ.*, 28, 185–188, [https://doi.org/https://doi.org/10.1016/1352-2310\(94\)90093-0](https://doi.org/https://doi.org/10.1016/1352-2310(94)90093-0), 1994.
- Peñuelas, J. and Staudt, M.: BVOCs and global change, *Trends Plant Sci.*, 15, 133–144, <https://doi.org/10.1016/j.tplants.2009.12.005>, 2010.
- Perkins, S. E.: A review on the scientific understanding of heatwaves—Their measurement, driving mechanisms, and changes at the global scale, *Atmos. Res.*, 164–165, 242–267, <https://doi.org/10.1016/j.atmosres.2015.05.014>, 2015.
- Perkins, S. E. and Alexander, L. V.: On the Measurement of Heat Waves, *J. Clim.*, 26, 4500–4517, <https://doi.org/10.1175/JCLI-D-12-00383.1>, 2013.
- Perkins, S. E., Alexander, L. V., and Nairn, J. R.: Increasing frequency, intensity and duration of observed global heatwaves and warm spells, *Geophys. Res. Lett.*, 39, 2012GL053361, <https://doi.org/10.1029/2012GL053361>, 2012.
- Perkins-Kirkpatrick, S. E. and Gibson, P. B.: Changes in regional heatwave characteristics as a function of increasing global temperature, *Sci. Rep.*, 7, 12256, <https://doi.org/10.1038/s41598-017-12520-2>, 2017.



- 1480 Perkins-Kirkpatrick, S. E. and Lewis, S. C.: Increasing trends in regional heatwaves, *Nat. Commun.*, 11, 3357, <https://doi.org/10.1038/s41467-020-16970-7>, 2020.
- Pfannerstill, E. Y., Arata, C., Zhu, Q., Schulze, B. C., Ward, R., Woods, R., Harkins, C., Schwantes, R. H., Seinfeld, J. H., Bucholtz, A., Cohen, R. C., and Goldstein, A. H.: Temperature-dependent emissions dominate aerosol and ozone formation in Los Angeles, *Science*, 384, 1324–1329, <https://doi.org/10.1126/science.adg8204>, 2024.
- 1485 Porter, W. C. and Heald, C. L.: The mechanisms and meteorological drivers of the summertime ozone–temperature relationship, *Atmos. Chem. Phys.*, 19, 13367–13381, <https://doi.org/10.5194/acp-19-13367-2019>, 2019.
- Presto, A. A., Miracolo, M. A., Kroll, J. H., Worsnop, D. R., Robinson, A. L., and Donahue, N. M.: Intermediate-Volatility Organic Compounds: A Potential Source of Ambient Oxidized Organic Aerosol, *Environ. Sci. Technol.*, 43, 4744–4749, <https://doi.org/10.1021/es803219q>, 2009.
- 1490 Previdi, M., Smith, K. L., and Polvani, L. M.: Arctic amplification of climate change: a review of underlying mechanisms, *Environ. Res. Lett.*, 16, 093003, <https://doi.org/10.1088/1748-9326/ac1c29>, 2021.
- Pu, X., Wang, T. J., Huang, X., Melas, D., Zanis, P., Papanastasiou, D. K., and Poupkou, A.: Enhanced surface ozone during the heat wave of 2013 in Yangtze River Delta region, China, *Sci. Total Environ.*, 603–604, 807–816, <https://doi.org/10.1016/j.scitotenv.2017.03.056>, 2017.
- 1495 Pusede, S. E. and Cohen, R. C.: On the observed response of ozone to NO_x and VOC reactivity reductions in San Joaquin Valley California 1995–present, *Atmos. Chem. Phys.*, 12, 8323–8339, <https://doi.org/10.5194/acp-12-8323-2012>, 2012.
- Pusede, S. E., Gentner, D. R., Wooldridge, P. J., Browne, E. C., Rollins, A. W., Min, K.-E., Russell, A. R., Thomas, J., Zhang, L., Brune, W. H., Henry, S. B., DiGangi, J. P., Keutsch, F. N., Harrold, S. A., Thornton, J. A., Beaver, M. R., St. Clair, J. M., Wennberg, P. O., Sanders, J., Ren, X., VandenBoer, T. C., Markovic, M. Z., Guha, A., Weber, R., Goldstein, A. H., and Cohen, R. C.: On the temperature dependence of organic reactivity, nitrogen oxides, ozone production, and the impact of emission controls in San Joaquin Valley, California, *Atmos. Chem. Phys.*, 14, 3373–3395, <https://doi.org/10.5194/acp-14-3373-2014>, 2014.
- 1500 Pye, H. O. T., Nenes, A., Alexander, B., Ault, A. P., Barth, M. C., Clegg, S. L., Collett Jr., J. L., Fahey, K. M., Hennigan, C. J., Herrmann, H., Kanakidou, M., Kelly, J. T., Ku, I.-T., McNeill, V. F., Riemer, N., Schaefer, T., Shi, G., Tilgner, A., Walker, J. T., Wang, T., Weber, R., Xing, J., Zaveri, R. A., and Zuend, A.: The acidity of atmospheric particles and clouds, *Atmos. Chem. Phys.*, 20, 4809–4888, <https://doi.org/10.5194/acp-20-4809-2020>, 2020.
- 1505 Qin, M., She, Y., Wang, M., Wang, H., Chang, Y., Tan, Z., An, J., Huang, J., Yuan, Z., Lu, J., Wang, Q., Liu, C., Liu, Z., Xie, X., Li, J., Liao, H., Pye, H. O. T., Huang, C., Guo, S., Hu, M., Zhang, Y., Jacob, D. J., and Hu, J.: Increased urban ozone in heatwaves due to temperature-induced emissions of anthropogenic volatile organic compounds, *Nat. Geosci.*, 18, 50–56, <https://doi.org/10.1038/s41561-024-01608-w>, 2025.
- 1510 Qu, F., Huang, Y., Shen, Y., Zhong, G., Xu, Y., Jin, L., Qian, H., Xiong, C., Zhang, F., Shen, J., Xu, B., Tian, X., Xu, Z., and Wang, Z.: Enhanced VOC emission with increased temperature contributes to the shift of O₃-precursors relationship and optimal control strategy, *J. Environ. Sci.*, 150, 218–229, <https://doi.org/10.1016/j.jes.2024.02.024>, 2025.
- 1515



- Ramamurthy, P. and Bou-Zeid, E.: Heatwaves and urban heat islands: A comparative analysis of multiple cities, *J. Geophys. Res. Atmos.*, 122, 168–178, <https://doi.org/10.1002/2016JD025357>, 2017.
- Robinson, P. J.: On the Definition of a Heat Wave, *J. Appl. Meteorol.*, 40, 762–775, [https://doi.org/10.1175/1520-0450\(2001\)040%3C0762:OTDOAH%3E2.0.CO;2](https://doi.org/10.1175/1520-0450(2001)040%3C0762:OTDOAH%3E2.0.CO;2), 2001.
- 1520 Rohini, P., Rajeevan, M., and Srivastava, A. K.: On the Variability and Increasing Trends of Heat Waves over India, *Sci. Rep.*, 6, 26153, <https://doi.org/10.1038/srep26153>, 2016.
- Röthlisberger, M. and Papritz, L.: Quantifying the physical processes leading to atmospheric hot extremes at a global scale, *Nat. Geosci.*, 16, 210–216, <https://doi.org/10.1038/s41561-023-01126-1>, 2023.
- Rousi, E., Kornhuber, K., Beobide-Arsuaga, G., Luo, F., and Coumou, D.: Accelerated western European heatwave trends linked to more-persistent double jets over Eurasia, *Nat. Commun.*, 13, 3851, <https://doi.org/10.1038/s41467-022-31432-y>, 2022.
- 1525 Royal Netherlands Meteorological Institute (KNMI): Hittogolven, Royal Netherlands Meteorological Institute, <https://www.knmi.nl/nederland-nu/klimatologie/lijsten/hittogolven> (last access: 14 September 2026), 2026.
- Rubin, J. I., Kean, A. J., Harley, R. A., Millet, D. B., and Goldstein, A. H.: Temperature dependence of volatile organic compound evaporative emissions from motor vehicles, *J. Geophys. Res. Atmos.*, 111, <https://doi.org/10.1029/2005JD006458>, 2006.
- 1530 Russo, S., Sillmann, J., and Fischer, E. M.: Top ten European heatwaves since 1950 and their occurrence in the coming decades, *Environ. Res. Lett.*, 10, 124003, <https://doi.org/10.1088/1748-9326/10/12/124003>, 2015.
- Salvador, C. M., Wood, J. D., Cochran, E., Seubert, H. A., Kamplain, B., Overby, S. S., Birdwell, K., Gu, L., and Mayes, M. A.: Measurement report: Extreme heat and wildfire emissions enhance volatile organic compounds in a temperate forest, *Atmos. Chem. Phys.*, 25, 16611–16629, <https://doi.org/10.5194/acp-25-16611-2025>, 2025.
- 1535 Schade, G. W., Solomon, S. J., Dellwik, E., Pilegaard, K., and Ladstätter-Weissenmayer, A.: Methanol and other VOC fluxes from a Danish beech forest during late springtime, *Biogeochemistry*, 106, 337–355, <https://doi.org/10.1007/s10533-010-9515-5>, 2011.
- Schervish, M. and Shiraiwa, M.: Impact of phase state and non-ideal mixing on equilibration timescales of secondary organic aerosol partitioning, *Atmos. Chem. Phys.*, 23, 221–233, <https://doi.org/10.5194/acp-23-221-2023>, 2023.
- 1540 Schmedding, R., Rasool, Q. Z., Zhang, Y., Pye, H. O. T., Zhang, H., Chen, Y., Surratt, J. D., Lopez-Hilfiker, F. D., Thornton, J. A., Goldstein, A. H., and Vizuete, W.: Predicting secondary organic aerosol phase state and viscosity and its effect on multiphase chemistry in a regional-scale air quality model, *Atmos. Chem. Phys.*, 20, 8201–8225, <https://doi.org/10.5194/acp-20-8201-2020>, 2020.
- 1545 Schnell, J. L. and Prather, M. J.: Co-occurrence of extremes in surface ozone, particulate matter, and temperature over eastern North America, *Proc. Natl. Acad. Sci.*, 114, 2854–2859, <https://doi.org/10.1073/pnas.1614453114>, 2017.
- Seco, R., Peñuelas, J., and Filella, I.: Short-chain oxygenated VOCs: Emission and uptake by plants and atmospheric sources, sinks, and concentrations, *Atmos. Environ.*, 41, 2477–2499,



- 1550 <https://doi.org/https://doi.org/10.1016/j.atmosenv.2006.11.029>, 2007.
- Seco, R., Holst, T., Davie-Martin, C. L., Simin, T., Guenther, A., Pirk, N., Rinne, J., and Rinnan, R.: Strong isoprene emission response to temperature in tundra vegetation, *Proc. Natl. Acad. Sci.*, 119, e2118014119, <https://doi.org/10.1073/pnas.2118014119>, 2022.
- Seltzer, K. M., Murphy, B. N., Pennington, E. A., Allen, C., Talgo, K., and Pye, H. O. T.: Volatile Chemical Product Enhancements to Criteria Pollutants in the United States, *Environ. Sci. Technol.*, 56, 6905–6913, <https://doi.org/10.1021/acs.est.1c04298>, 2021.
- 1555 Serrano Damha, C., Cummings, B. E., Schervish, M., Shiraiwa, M., Waring, M. S., and Zuend, A.: Capturing the Relative-Humidity-Sensitive Gas–Particle Partitioning of Organic Aerosols in a 2D Volatility Basis Set, *Geophys. Res. Lett.*, 51, e2023GL106095, <https://doi.org/https://doi.org/10.1029/2023GL106095>, 2024.
- 1560 Sfindla, Y., Stavrou, T., Müller, J.-F., Oomen, G.-M., Opacka, B., Danckaert, T., De Smedt, I., and Lerot, C.: Global VOC emissions quantified from inversion of TROPOMI spaceborne formaldehyde and glyoxal data, *Atmos. Chem. Phys.*, 26, 733–767, <https://doi.org/10.5194/acp-26-733-2026>, 2026.
- Shahin, M., Kammer, J., Temime-Roussel, B., and D’Anna, B.: Gas–particle partitioning of m-xylene and naphthalene oxidation products: temperature and NO_x influence, *Atmos. Chem. Phys.*, 25, 10267–10292, <https://doi.org/10.5194/acp-25-10267-2025>, 2025.
- 1565 Shan, L., Wang, N., Duan, F., Zhang, S., Duan, L., Zhang, Q., Zhu, L., Wang, S., Jiang, J., Ma, Y., and He, K.: Global heatwaves: A scoping review on the trend, characteristics, impacts on air pollution and health, *Environ. Res.*, 286, 122976, <https://doi.org/https://doi.org/10.1016/j.envres.2025.122976>, 2025.
- Shen, C., Yang, X., Thornton, J., Shilling, J., Bi, C., Isaacman-VanWertz, G., and Zhang, H.: Observation-constrained kinetic modeling of isoprene SOA formation in the atmosphere, *Atmos. Chem. Phys.*, 24, 6153–6175, <https://doi.org/10.5194/acp-24-6153-2024>, 2024.
- Shiraiwa, M. and Pöschl, U.: Mass accommodation and gas–particle partitioning in secondary organic aerosols: dependence on diffusivity, volatility, particle-phase reactions, and penetration depth, *Atmos. Chem. Phys.*, 21, 1565–1580, <https://doi.org/10.5194/acp-21-1565-2021>, 2021.
- 1575 Sillman, S.: The relation between ozone, NO_x and hydrocarbons in urban and polluted rural environments, *Atmos. Environ.*, 33, 1821–1845, [https://doi.org/https://doi.org/10.1016/S1352-2310\(98\)00345-8](https://doi.org/https://doi.org/10.1016/S1352-2310(98)00345-8), 1999.
- Sindelarova, K., Granier, C., Bouarar, I., Guenther, A., Tilmes, S., Stavrou, T., Müller, J.-F., Kuhn, U., Stefani, P., and Knorr, W.: Global data set of biogenic VOC emissions calculated by the MEGAN model over the last 30 years, *Atmos. Chem. Phys.*, 14, 9317–9341, <https://doi.org/10.5194/acp-14-9317-2014>, 2014.
- 1580 Song, C., Liu, B., Dai, Q., Li, H., and Mao, H.: Temperature dependence and source apportionment of volatile organic compounds (VOCs) at an urban site on the north China plain, *Atmos. Environ.*, 207, 167–181, <https://doi.org/https://doi.org/10.1016/j.atmosenv.2019.03.030>, 2019.
- Srivastava, D., Vu, T. V., Tong, S., Shi, Z., and Harrison, R. M.: Formation of secondary organic aerosols from anthropogenic precursors in laboratory studies, *Npj Clim. Atmos. Sci.*, 5, 22, <https://doi.org/10.1038/s41612-022->



1585 00238-6, 2022.

Staudt, M., Bourgeois, I., Halabi, R. A., Song, W., and Williams, J.: New insights into the parametrization of temperature and light responses of mono - and sesquiterpene emissions from Aleppo pine and rosemary, *Atmos. Environ.*, 152, 212–221, <https://doi.org/https://doi.org/10.1016/j.atmosenv.2016.12.033>, 2017.

1590 Stavrakou, T., Müller, J.-F., De Smedt, I., Van Roozendaal, M., van der Werf, G. R., Giglio, L., and Guenther, A.: Global emissions of non-methane hydrocarbons deduced from SCIAMACHY formaldehyde columns through 2003–2006, *Atmos. Chem. Phys.*, 9, 3663–3679, <https://doi.org/https://doi.org/10.5194/acp-9-3663-2009>, 2009.

1595 Stavrakou, T., Müller, J.-F., Bauwens, M., De Smedt, I., Van Roozendaal, M., De Mazière, M., Vigouroux, C., Hendrick, F., George, M., Clerbaux, C., Coheur, P.-F., and Guenther, A.: How consistent are top-down hydrocarbon emissions based on formaldehyde observations from GOME-2 and OMI?, *Atmos. Chem. Phys.*, 15, 11861–11884, <https://doi.org/https://doi.org/10.5194/acp-15-11861-2015>, 2015.

Stavrakou, T., Müller, J.-F., Bauwens, M., De Smedt, I., Van Roozendaal, M., and Guenther, A.: Impact of Short-Term Climate Variability on Volatile Organic Compounds Emissions Assessed Using OMI Satellite Formaldehyde Observations, *Geophys. Res. Lett.*, 45, 8681–8689, <https://doi.org/https://doi.org/10.1029/2018GL078676>, 2018.

1600 Su, J., Jiao, L., and Xu, G.: Intensified exposure to compound extreme heat and ozone pollution in summer across Chinese cities, *Npj Clim. Atmos. Sci.*, 8, 78, <https://doi.org/https://doi.org/10.1038/s41612-025-00966-5>, 2025.

Su, Q. and Dong, B.: Recent Decadal Changes in Heat Waves over China: Drivers and Mechanisms, *J. Clim.*, 32, 4215–4234, <https://doi.org/https://doi.org/10.1175/JCLI-D-18-0479.1>, 2019.

1605 Sun, X., Shi, C., Zhang, H., Wang, Z., Zhao, T., Ning, G., Lu, Y., Yang, Q., and Gao, F.: Differentiated evolutions of co-occurrence of extreme heat and ozone pollution over the middle-lower Yangtze River basin during 2018–2024, *Atmos. Res.*, 336, 108911, <https://doi.org/https://doi.org/10.1016/j.atmosres.2026.108911>, 2026.

Tan, Y., Zhi, Y., Gao, M., Cheng, Z., Yan, B., Nie, L., Chen, G., and Hou, L.: Influence of temperature on formaldehyde emission parameters of solvent-based coatings, *J. Coat. Technol. Res.*, 18, 677–684, <https://doi.org/https://doi.org/10.1007/s11998-020-00432-2>, 2021.

1610 Thirumalai, K., DiNezio, P. N., Okumura, Y., and Deser, C.: Extreme temperatures in Southeast Asia caused by El Niño and worsened by global warming, *Nat. Commun.*, 8, 15531, <https://doi.org/https://doi.org/10.1038/ncomms15531>, 2017.

Thomas, N. P., Bosilovich, M. G., Marquardt Collow, A. B., Koster, R. D., Schubert, S. D., Dezfuli, A., and Mahanama, S. P.: Mechanisms Associated with Daytime and Nighttime Heat Waves over the Contiguous United States, *J. Appl. Meteorol. Climatol.*, 59, 1865–1882, <https://doi.org/https://doi.org/10.1175/JAMC-D-20-0053.1>, 2020.

1615 Tilgner, A., Schaefer, T., Alexander, B., Barth, M., Collett Jr., J. L., Fahey, K. M., Nenes, A., Pye, H. O. T., Herrmann, H., and McNeill, V. F.: Acidity and the multiphase chemistry of atmospheric aqueous particles and clouds, *Atmos. Chem. Phys.*, 21, 13483–13536, <https://doi.org/https://doi.org/10.5194/acp-21-13483-2021>, 2021.

Tsimpidi, A. P., Scholz, S. M. C., Milousis, A., Mihalopoulos, N., and Karydis, V. A.: Aerosol composition trends during 2000–2020: in-depth insights from model predictions and multiple worldwide near-surface observation datasets, *Atmos. Chem. Phys.*, 25, 10183–10213, <https://doi.org/https://doi.org/10.5194/acp-25-10183-2025>, 2025.



- 1620 Tudor, C.: Ozone pollution in London and Edinburgh: spatiotemporal characteristics, trends, transport and the impact of COVID-19 control measures, *Heliyon*, 8, <https://doi.org/10.1016/j.heliyon.2022.e11384>, 2022.
- US Environmental Protection Agency (EPA): AP-42 Compilation of Air Pollutant Emission Factors, Chapter 7: Liquid Storage Tanks, U.S. Environmental Protection Agency, Research Triangle Park, NC, <https://www.epa.gov/air-emissions-factors-and-quantification/final-revisions-ap-42-chapter-7-section-1-organic-liquid> (last access: 27 July 2026), 2024.
- 1625 U.S. Environmental Protection Agency (EPA): Climate Change Indicators in the United States, Fifth Edition, U.S. Environmental Protection Agency, <https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockkey=P101AXFE.txt> (last access: 14 September 2026), 2024.
- Wang, C., Li, Z., Chen, Y., Li, Y., Ouyang, L., Zhu, J., Sun, F., Song, S., and Li, H.: Changes in Global Heatwave Risk and Its Drivers Over One Century, *Earths Future*, 12, e2024EF004430, <https://doi.org/10.1029/2024EF004430>, 2024a.
- 1630 Wang, C., Zhang, S., Zhang, Y., Cui, S., Qin, X., Guenther, A., Bai, J., Gu, D., Du, J., Tang, J., Yao, W., Wang, M., and Sun, Y.: VOCs-driven ozone extremes during dry and wet heatwaves in the Jiangsu–Shandong–Henan–Anhui Boundary: Integrating meteorological forcings and SHAP interpretation, *Atmos. Res.*, 328, 108396, <https://doi.org/https://doi.org/10.1016/j.atmosres.2025.108396>, 2026a.
- 1635 Wang, H., Wu, K., Liu, Y., Sheng, B., Lu, X., He, Y., Xie, J., Wang, H., and Fan, S.: Role of Heat Wave-Induced Biogenic VOC Enhancements in Persistent Ozone Episodes Formation in Pearl River Delta, *J. Geophys. Res. Atmos.*, 126, e2020JD034317, <https://doi.org/https://doi.org/10.1029/2020JD034317>, 2021a.
- Wang, H., Welch, A., Nagalingam, S., Leong, C., Kittitanuvong, P., Barsanti, K. C., Sheesley, R. J., Czimeczik, C. I., and Guenther, A. B.: Arctic Heatwaves Could Significantly Influence the Isoprene Emissions From Shrubs, *Geophys. Res. Lett.*, 51, e2023GL107599, <https://doi.org/https://doi.org/10.1029/2023GL107599>, 2024b.
- 1640 Wang, H., Liu, X., Wu, C., and Lin, G.: Regional to global distributions, trends, and drivers of biogenic volatile organic compound emission from 2001 to 2020, *Atmos. Chem. Phys.*, 24, 3309–3328, <https://doi.org/10.5194/acp-24-3309-2024>, 2024c.
- 1645 Wang, L., Yang, X., Dong, J., Yang, Y., Ma, P., and Zhao, W.: Evolution of surface ozone pollution pattern in eastern China and its relationship with different intensity heatwaves, *Environ. Pollut.*, 338, 122725, <https://doi.org/https://doi.org/10.1016/j.envpol.2023.122725>, 2023.
- Wang, N., Du, Y., Chen, D., Meng, H., Chen, X., Zhou, L., Shi, G., Zhan, Y., Feng, M., Li, W., Chen, M., Li, Z., and Yang, F.: Spatial disparities of ozone pollution in the Sichuan Basin spurred by extreme, hot weather, *Atmos. Chem. Phys.*, 24, 3029–3042, <https://doi.org/10.5194/acp-24-3029-2024>, 2024d.
- 1650 Wang, N., Duan, F., Shan, L., Zhang, S., Ma, Y., Zhang, Q., Zhu, L., Wang, S., Jiang, J., Huang, T., Kimoto, T., and He, K.: Impacts of Intensified Heatwaves on Escalation of Ozone and Reactive Nitrogen in Summer, *Environ. Sci. Technol.*, 60, 887–901, <https://doi.org/10.1021/acs.est.5c09309>, 2026b.
- Wang, P., Tang, J., Sun, X., Wang, S., Wu, J., Dong, X., and Fang, J.: Heat Waves in China: Definitions, Leading Patterns, and Connections to Large-Scale Atmospheric Circulation and SSTs, *J. Geophys. Res. Atmos.*, 122,
- 1655



- <https://doi.org/10.1002/2017JD027180>, 2017.
- Wang, P., Chen, Y., Hu, J., Zhang, H., and Ying, Q.: Attribution of Tropospheric Ozone to NO_x and VOC Emissions: Considering Ozone Formation in the Transition Regime, *Environ. Sci. Technol.*, 53, 1404–1412, <https://doi.org/10.1021/acs.est.8b05981>, 2019.
- 1660 Wang, P., Wang, Y., Huang, T., and Zhang, H.: A global assessment of intensified heatwaves and air quality, *Cell Rep. Sustain.*, 3, <https://doi.org/10.1016/j.crsus.2025.100559>, 2026c.
- Wang, P., Yu, W., Zhang, Z., Feng, M., Gao, M., Tian, C., Wang, Y., Guenther, A., Zhang, Y., Li, Z., Fu, P., Carmichael, G. R., Zhang, H., Chen, J., Zhang, R., and Shindell, D.: Coupled biogenic and soil emissions amplify heatwave-driven secondary pollution, *Environ. Sci. Ecotechnology*, 32, 100720, <https://doi.org/10.1016/j.ese.2026.100720>, 2026d.
- 1665 Wang, P., Yu, W., Zhang, Z., Lu, J., Li, S., and Zhang, H.: Direct thermal enhancement dominates over emission-mediated pathways in heatwave-induced O₃ and SOA increases across China, *EGUsphere*, 2026, 1–20, <https://doi.org/10.5194/egusphere-2026-1101>, 2026e.
- Wang, W., Li, X., Cheng, Y., Parrish, D. D., Ni, R., Tan, Z., Liu, Y., Lu, S., Wu, Y., Chen, S., Lu, K., Hu, M., Zeng, L., Shao, M., Huang, C., Tian, X., Leung, K. M., Chen, L., Fan, M., Zhang, Q., Rohrer, F., Wahner, A., Pöschl, U., Su, H., and Zhang, Y.: Ozone pollution mitigation strategy informed by long-term trends of atmospheric oxidation capacity, *Nat. Geosci.*, 17, 20–25, <https://doi.org/10.1038/s41561-023-01334-9>, 2024e.
- 1670 Wang, W., Su, H., Parrish, D. D., Ni, R., Li, X., Bao, F., Wang, H., Huang, C., Williams, J., Liao, H., Lu, K., Zhang, Y., and Cheng, Y.: Global warming makes nitrogen oxide abatement key to ozone pollution mitigation, *Sci. Adv.*, 12, eaea4124, <https://doi.org/10.1126/sciadv.aea4124>, 2026f.
- 1675 Wang, W., Su, H., Huang, X., Zeng, C., Parrish, D. D., Zhang, Y., Ding, A., and Cheng, Y.: The dominant role of temperature in seasonal ozone sensitivity changes in China, *Nat. Geosci.*, <https://doi.org/10.1038/s41561-026-02036-8>, 2026g.
- Wang, X., Yin, S., Zhang, R., Yuan, M., and Ying, Q.: Assessment of summertime O₃ formation and the O₃-NO_x-VOC sensitivity in Zhengzhou, China using an observation-based model, *Sci. Total Environ.*, 813, 152449, <https://doi.org/10.1016/j.scitotenv.2021.152449>, 2022.
- 1680 Wang, X., Zhang, R., Fu, Z.-H., Zhou, Z.-Q., Zhang, Y., and Jin, D.: Record-Breaking Summertime Terrestrial and Marine Heat Waves in Southeast Asia Driven by Internal Variability during 2020–22, *J. Clim.*, 39, 51–63, <https://doi.org/10.1175/JCLI-D-25-0202.1>, 2026h.
- 1685 Wang, Y., Ji, Z., Xie, Q., Teng, Q., Tang, Y., and Bai, Y.: Analysis of factors affecting VOCs emission from oil storage processes, *J. Environ. Eng. Technol.*, 11, 523–529, 2021b.
- Wang, Y., Bastien, L. A. J., Wang, Y., Jin, L., and Harley, R. A.: Temperature and stagnation effects on ozone sensitivity to NO_x and VOC: an adjoint modeling study in central California, *Atmos. Chem. Phys.*, 25, 17651–17665, <https://doi.org/10.5194/acp-25-17651-2025>, 2025.
- 1690 Wang, Y., Ho, J. Y., Guo, Y., Jin, L. N., and Ren, C.: Effect of compound heat and ozone events on health outcomes:



- a systematic review and meta-analysis of epidemiological evidence, *Environ. Pollut.*, 390, 127570, <https://doi.org/10.1016/j.envpol.2025.127570>, 2026i.
- Wei, J., Wang, W., Wang, G., Cao, M., Yang, L., Zhang, S., Fu, J., and Xing, W.: Projecting the Changes in Multifaceted Characteristics of Heatwave Events Across China, *Earths Future*, 11, e2022EF003387, <https://doi.org/https://doi.org/10.1029/2022EF003387>, 2023.
- Wei, J., Wang, W., Teuling, A. J., Zhang, J., Wang, G., Jin, J., Liu, X., Cao, M., Li, H., Yang, L., and Wang, S.: Reduced Anthropogenic Aerosols Reveal Increased Heatwaves Driven by Climate Warming, *Earths Future*, 13, e2025EF006516, <https://doi.org/10.1029/2025EF006516>, 2025.
- Werner, C., Fasbender, L., Romek, K. M., Yáñez-Serrano, A. M., and Kreuzwieser, J.: Heat Waves Change Plant Carbon Allocation Among Primary and Secondary Metabolism Altering CO₂ Assimilation, Respiration, and VOC Emissions, *Front. Plant Sci.*, 11, 1242, <https://doi.org/10.3389/fpls.2020.01242>, 2020.
- Whalley, L. K., Slater, E. J., Woodward-Massey, R., Ye, C., Lee, J. D., Squires, F., Hopkins, J. R., Dunmore, R. E., Shaw, M., Hamilton, J. F., Lewis, A. C., Mehra, A., Worrall, S. D., Bacak, A., Bannan, T. J., Coe, H., Percival, C. J., Ouyang, B., Jones, R. L., Crilley, L. R., Kramer, L. J., Bloss, W. J., Vu, T., Kotthaus, S., Grimmond, S., Sun, Y., Xu, W., Yue, S., Ren, L., Acton, W. J. F., Hewitt, C. N., Wang, X., Fu, P., and Heard, D. E.: Evaluating the sensitivity of radical chemistry and ozone formation to ambient VOCs and NO_x in Beijing, *Atmos. Chem. Phys.*, 21, 2125–2147, <https://doi.org/10.5194/acp-21-2125-2021>, 2021.
- Wu, W., Liu, Q., Li, H., and Huang, C.: Spatiotemporal Distribution of Heatwave Hazards in the Chinese Mainland for the Period 1990–2019, *Int. J. Environ. Res. Public. Health*, 20, 1532, <https://doi.org/10.3390/ijerph20021532>, 2023a.
- Wu, W., Fu, T.-M., Arnold, S. R., Spracklen, D. V., Zhang, A., Tao, W., Wang, X., Hou, Y., Mo, J., Chen, J., Li, Y., Feng, X., Lin, H., Huang, Z., Zheng, J., Shen, H., Zhu, L., Wang, C., Ye, J., and Yang, X.: Temperature-Dependent Evaporative Anthropogenic VOC Emissions Significantly Exacerbate Regional Ozone Pollution, *Environ. Sci. Technol.*, 58, 5430–5441, <https://doi.org/10.1021/acs.est.3c09122>, 2024.
- Wu, Y., Fan, X., Liu, Y., Zhang, J., Wang, H., Sun, L., Fang, T., Mao, H., Hu, J., Wu, L., Peng, J., and Wang, S.: Source apportionment of VOCs based on photochemical loss in summer at a suburban site in Beijing, *Atmos. Environ.*, 293, 119459, <https://doi.org/https://doi.org/10.1016/j.atmosenv.2022.119459>, 2023b.
- Xian, Y., Wang, N., Liu, S., and Yang, F.: Natural and Anthropogenic Temperature-Sensitive Emissions Amplify Ozone Pollution under Heatwaves in the Sichuan Basin, *Environ. Sci. Technol.*, <https://doi.org/10.1021/acs.est.6c05307>, 2026.
- Xie, W. and Zhou, B.: On the atmospheric background for the occurrence of three heat wave types in East China, *Weather Clim. Extrem.*, 39, 100539, <https://doi.org/10.1016/j.wace.2022.100539>, 2023.
- Xiong, J., Wei, W., Huang, S., and Zhang, Y.: Association between the Emission Rate and Temperature for Chemical Pollutants in Building Materials: General Correlation and Understanding, *Environ. Sci. Technol.*, 47, 8540–8547, <https://doi.org/10.1021/es401173d>, 2013.
- Xu, C., Jin, J., Li, K., Qi, Y., Xia, J., Lin, H. X., and Liao, H.: NMVOC emission optimization in China through



assimilating formaldehyde retrievals from multiple satellite products, *Atmos. Chem. Phys.*, 26, 33–58, <https://doi.org/10.5194/acp-26-33-2026>, 2026.

1730 Xu, R., Ma, H., Li, J., Tong, D., Yan, L., Wang, L., Qin, X., Xiao, Q., Yan, X., Hu, H., Fu, Y., Wu, N., Wang, H., Wang, Y., Liu, X., Geng, G., He, K., and Zhang, Q.: A technology-based global non-methane volatile organic compounds (NMVOC) emission inventory\ under the MEIC framework, *Atmos. Chem. Phys.*, 25, 12675–12700, <https://doi.org/10.5194/acp-25-12675-2025>, 2025.

1735 Xu, Z., FitzGerald, G., Guo, Y., Jalaludin, B., and Tong, S.: Impact of heatwave on mortality under different heatwave definitions: A systematic review and meta-analysis, *Environ. Int.*, 89–90, 193–203, <https://doi.org/10.1016/j.envint.2016.02.007>, 2016.

Yan, L., Zheng, B., Geng, G., Hong, C., Tong, D., and Zhang, Q.: Evaporation process dominates vehicular NMVOC emissions in China with enlarged contribution from 1990 to 2016, *Environ. Res. Lett.*, 16, 124036, <https://doi.org/10.1088/1748-9326/ac3872>, 2021.

1740 Yáñez-Serrano, A. M., Mahlau, L., Fasbender, L., Byron, J., Williams, J., Kreuzwieser, J., and Werner, C.: Heat stress increases the use of cytosolic pyruvate for isoprene biosynthesis, *J. Exp. Bot.*, 70, 5827–5838, <https://doi.org/10.1093/jxb/erz353>, 2019.

1745 Yang, H., Ren, B., Huang, Y., Zhang, Z., Hu, W., Liu, M., Zhao, H., Jiang, G., and Hao, Z.: Volatile organic compounds (VOCs) emissions from internal floating-roof tank in oil depots in Beijing: Influencing factors and emission reduction strategies analysis, *Sci. Total Environ.*, 916, 170222, <https://doi.org/https://doi.org/10.1016/j.scitotenv.2024.170222>, 2024.

Yang, J., Yin, P., Sun, J., Wang, B., Zhou, M., Li, M., Tong, S., Meng, B., Guo, Y., and Liu, Q.: Heatwave and mortality in 31 major Chinese cities: Definition, vulnerability and implications, *Sci. Total Environ.*, 649, 695–702, <https://doi.org/10.1016/j.scitotenv.2018.08.332>, 2019.

1750 Yang, L., Nie, W., Yan, C., Ehn, M., Liu, Y., Roldin, P., Qi, X., Kerminen, V.-M., Donahue, N. M., Worsnop, D., Kulmala, M., and Ding, A.: A mechanistic understanding of the varying yields of highly oxygenated organic molecules, *Nat. Commun.*, 17, 302, <https://doi.org/10.1038/s41467-025-67007-w>, 2025.

Yang, Y., Liu, B., Hua, J., Yang, T., Dai, Q., Wu, J., Feng, Y., and Hopke, P. K.: Global review of source apportionment of volatile organic compounds based on highly time-resolved data from 2015 to 2021, *Environ. Int.*, 165, 107330, <https://doi.org/10.1016/j.envint.2022.107330>, 2022.

1755 Yang, Y., Sun, F., Chen, Y., Yang, S., Dai, Y., Qin, Y., Zhang, N., Shu, Z., Yan, H., Ge, X., and Wang, J.: Impact of temperature on the biogenic volatile organic compound (BVOC) emissions in China: A review, *J. Environ. Sci.*, 159, 649–660, <https://doi.org/https://doi.org/10.1016/j.jes.2025.03.054>, 2026a.

1760 Yang, Z., Sha, T., Wu, F., Chen, Q., Boersma, K. F., Wang, J., and Zhang, Y.-L.: Underappreciated Soil NO_x Emissions Amplify Background O₃ Pollution During Compound Dry-Hot Extremes in North China, *Environ. Sci. Technol.*, <https://doi.org/10.1021/acs.est.6c06361>, 2026b.

Yao, Y., Wang, J., Yin, J., and Zou, X.: Marine Heatwaves in China's Marginal Seas and Adjacent Offshore Waters: Past, Present, and Future, *J. Geophys. Res. Oceans*, 125, e2019JC015801, <https://doi.org/10.1029/2019JC015801>,



2020.

1765 Ye, C., Lu, K., Ma, X., Qiu, W., Li, S., Yang, X., Xue, C., Zhai, T., Liu, Y., Li, X., Li, Y., Wang, H., Tan, Z., Chen, X., Dong, H., Zeng, L., Hu, M., and Zhang, Y.: HONO chemistry at a suburban site during the EXPLORE-YRD campaign in 2018: formation mechanisms and impacts on O₃ production, *Atmos. Chem. Phys.*, 23, 15455–15472, <https://doi.org/10.5194/acp-23-15455-2023>, 2023.

1770 Yeo, J.-H., Ha, K.-J., Kam, J., Chung, E.-S., Kim, D., and Franzke, C. L. E.: Dual regimes of North American heatwaves and their future change, *Weather Clim. Extrem.*, 53, 100912, <https://doi.org/10.1016/j.wace.2026.100912>, 2026.

Yin, L., Zheng, Y., Bai, B., Zhang, B., Silvern, R. F., Mao, J., Mickley, L. J., and Liu, P.: Processes driving the regional sensitivities of summertime PM_{2.5} to temperature across the US: new insights from model simulations, *Atmos. Chem. Phys.*, 26, 5901–5923, <https://doi.org/10.5194/acp-26-5901-2026>, 2026.

1775 Yuan, B., Shao, M., de Gouw, J., Parrish, D. D., Lu, S., Wang, M., Zeng, L., Zhang, Q., Song, Y., Zhang, J., and Hu, M.: Volatile organic compounds (VOCs) in urban air: How chemistry affects the interpretation of positive matrix factorization (PMF) analysis, *J. Geophys. Res. Atmos.*, 117, <https://doi.org/https://doi.org/10.1029/2012JD018236>, 2012.

1780 Yue, T., Wang, M., Huang, Z., Wang, X., Wang, Z., Wang, B., Zhang, L., and Wang, S.: Characteristics of evaporative emissions from light-duty vehicles and effects of ambient temperature on evaporative emissions of light-duty vehicles, *Res. Environ. Sci.*, 33, 73–81, <https://doi.org/10.13198/j.issn.1001-6929.2019.07.25>, 2020.

Zang, N., Zhao, J., Yan, P., Zhang, H., Tang, S., and Feng, G.: Interdecadal variations of persistent extreme heat events in eastern China under global warming, *Theor. Appl. Climatol.*, 146, 349–364, <https://doi.org/10.1007/s00704-021-03723-9>, 2021.

1785 Zeng, J., Zhang, Y., Pang, W., Ran, H., Guo, H., Lu, Y., Song, W., and Wang, X.: Heatwaves Suppress Isoprene Emission Optima in Subtropical Eucalyptus: Implications for Biogenic VOC Modeling Under Extreme Thermal Events, *Geophys. Res. Lett.*, 52, e2025GL114767, <https://doi.org/https://doi.org/10.1029/2025GL114767>, 2025.

Zeng, J., Wang, X., Lu, Y., Pang, W., Song, W., Zhang, Y., Peng, P., and Wang, X.: Heatwaves favour acyclic monoterpene emissions in tropical forests, *Nat. Commun.*, <https://doi.org/10.1038/s41467-026-77087-x>, 2026a.

1790 Zeng, L., Liu, Q., Huang, D. D., Lai, R. W. S., Shi, H., Hoi, K. I., Mok, K. M., and Li, Y. J.: Secondary Organic Aerosol Formation During Continental to Oceanic Transition in South China Coast: Effects of Photostationary State, Aqueous-Phase Processes, and Heatwaves, *J. Geophys. Res. Atmos.*, 131, e2025JD046027, <https://doi.org/https://doi.org/10.1029/2025JD046027>, 2026b.

1795 Zhang, G., Yu, X., Yin, H., Feng, C., Ma, C., Sun, S., Cheng, H., Wang, S., Shang, K., and Liu, X.: Heatwave-amplified atmospheric oxidation in a multi-province border area in Xuzhou, China, *Front. Environ. Sci.*, Volume 12-2024, <https://doi.org/10.3389/fenvs.2024.1496584>, 2024a.

Zhang, J., Shrivastava, M., Zelenyuk, A., Zaveri, R. A., Surratt, J. D., Riva, M., Bell, D., and Glasius, M.: Observationally Constrained Modeling of the Reactive Uptake of Isoprene-Derived Epoxydiols under Elevated Relative Humidity and Varying Acidity of Seed Aerosol Conditions, *ACS Earth Space Chem.*, 7, 788–799,



<https://doi.org/10.1021/acsearthspacechem.2c00358>, 2023.

1800 Zhang, Y., Chen, Y., Lambe, A. T., Olson, N. E., Lei, Z., Craig, R. L., Zhang, Z., Gold, A., Onasch, T. B., Jayne, J. T., Worsnop, D. R., Gaston, C. J., Thornton, J. A., Vizuete, W., Ault, A. P., and Surratt, J. D.: Effect of the Aerosol-Phase State on Secondary Organic Aerosol Formation from the Reactive Uptake of Isoprene-Derived Epoxidiols (IEPOX), *Environ. Sci. Technol. Lett.*, 5, 167–174, <https://doi.org/10.1021/acs.estlett.8b00044>, 2018.

1805 Zhang, Y., Yang, X., Wang, Y., Yang, Z., Zhao, H., and Ding, Y.: Light-duty vehicle organic gas emissions from tailpipe and evaporation: A review of influencing factors, *Sci. Total Environ.*, 947, 174523, <https://doi.org/10.1016/j.scitotenv.2024.174523>, 2024b.

Zhang, Z., Xu, W., Zeng, S., Liu, Y., Liu, T., Zhang, Y., Du, A., Li, Y., Zhang, N., Wang, J., Aruffo, E., Han, P., Li, J., Wang, Z., and Sun, Y.: Secondary Organic Aerosol Formation from Ambient Air in Summer in Urban Beijing: Contribution of S/IVOCs and Impacts of Heat Waves, *Environ. Sci. Technol. Lett.*, 11, 738–745, <https://doi.org/10.1021/acs.estlett.4c00415>, 2024c.

1810

Zhao, K., Bao, Y., Huang, J., Wu, Y., Moshary, F., Arend, M., Wang, Y., and Lee, X.: A high-resolution modeling study of a heat wave-driven ozone exceedance event in New York City and surrounding regions, *Atmos. Environ.*, 199, 368–379, <https://doi.org/10.1016/j.atmosenv.2018.10.059>, 2019.

Zhou, W., Xie, S.-P., and Yang, D.: Enhanced equatorial warming causes deep-tropical contraction and subtropical monsoon shift, *Nat. Clim. Change*, 9, 834–839, <https://doi.org/10.1038/s41558-019-0603-9>, 2019.

1815

Zhou, W., Hu, R., Xie, P., Guo, J., Shen, C., Cai, H., Guo, J., and Liu, X.: Assessment of ozone formation, precursor sensitivity, and pollution control under Heatwaves: Based on direct OPR observations, *Environ. Res.*, 303, 124718, <https://doi.org/10.1016/j.envres.2026.124718>, 2026.

Zhou, X., Li, M., Huang, X., Liu, T., Zhang, H., Qi, X., Wang, Z., Qin, Y., Geng, G., and Wang, J.: Urban meteorology–chemistry coupling in compound heat–ozone extremes, *Nat. Cities*, 2, 847–856, 2025.

1820

Zhu, Q., Schwantes, R. H., Coggon, M., Harkins, C., Schnell, J., He, J., Pye, H. O. T., Li, M., Baker, B., Moon, Z., Ahmadv, R., Pfannerstill, E. Y., Place, B., Wooldridge, P., Schulze, B. C., Arata, C., Bucholtz, A., Seinfeld, J. H., Warneke, C., Stockwell, C. E., Xu, L., Zuraski, K., Robinson, M. A., Neuman, J. A., Veres, P. R., Peischl, J., Brown, S. S., Goldstein, A. H., Cohen, R. C., and McDonald, B. C.: A better representation of volatile organic compound chemistry in WRF-Chem and its impact on ozone over Los Angeles, *Atmos. Chem. Phys.*, 24, 5265–5286, <https://doi.org/10.5194/acp-24-5265-2024>, 2024.

1825

Zhu, S., Zhang, J., Li, L., Zhou, M., Qiao, L., Wang, H., Huang, D. D., Wang, Q., Jing, S., Wu, Y., Wang, S., Chen, C., Ying, Q., and Yu, J. Z.: Aerosol Uptake Coefficients of Isoprene Epoxides: Determination and Parameter Estimation from Online Field Measurements of Organic Molecular Markers, *Environ. Sci. Technol.*, 59, 18249–18258, <https://doi.org/10.1021/acs.est.5c09046>, 2025.

1830

Zuend, A. and Seinfeld, J. H.: Modeling the gas-particle partitioning of secondary organic aerosol: the importance of liquid-liquid phase separation, *Atmos. Chem. Phys.*, 12, 3857–3882, <https://doi.org/10.5194/acp-12-3857-2012>, 2012.



Table 1 Heatwave definition criteria of different organizations worldwide.

Institutions	Temperature thresholds	Durations	References
Intergovernmental Panel on Climate Change (IPCC)	Abnormally hot weather, often defined using relative temperature thresholds	2 days to months	(Intergovernmental Panel On Climate Change (Ipcc), 2023b)
World Health Organization (WHO)	Unusually hot and dry or hot and humid conditions relative to the local climate	≥ 2 days	(McGregor et al., 2015)
Korea Meteorological Administration (KMA)	Daily maximum feels-like temperature $>33^{\circ}\text{C}$	—	(KMA, 2026)
Royal Netherlands Meteorological Institute (KNMI)	Temperature $\geq 25^{\circ}\text{C}$ for 5 consecutive days, including at least 3 days with temperatures $\geq 30^{\circ}\text{C}$	≥ 5 days	(KNMI, 2026)
China Meteorological Administration (CMA)	Daily maximum temperature $\geq 35^{\circ}\text{C}$	≥ 3 days	(CMA, 2018)
U.S. Environmental Protection Agency (EPA)	Daily minimum apparent temperature above the 85th percentile of the local historical temperature distribution for July-August during 1981-2010	≥ 2 days	(EPA, 2024)
German Weather Service (DWD)	Strong heat stress is defined by a perceived temperature of approximately $>32^{\circ}\text{C}$, combined with insufficient nighttime cooling; extreme heat stress occurs at $>38^{\circ}\text{C}$.	≥ 2 days	(DWD, 2024)
Spanish State Meteorological Agency (AEMET)	Daily maximum temperature exceeds the 95th percentile of the station-specific July-August temperature distribution for 1971-2000 at $\geq 10\%$ of meteorological stations.	≥ 3 days	(AEMET, 2024)
India Meteorological Department (IMD)	Plains: $T_{\text{max}} \geq 40^{\circ}\text{C}$; hilly regions: $T_{\text{max}} \geq 30^{\circ}\text{C}$; Heat Wave: T_{max} departure from normal $4.5\text{--}6.4^{\circ}\text{C}$ or actual $T_{\text{max}} \geq 45^{\circ}\text{C}$; for coastal stations, Heat Wave may be described when T_{max} departure from normal $\geq 4.5^{\circ}\text{C}$ and actual $T_{\text{max}} \geq 37^{\circ}\text{C}$.	≥ 2 days at ≥ 2 stations	(IMD, 2021)



Table 2 Research methods for investigating the effects of heatwaves on VOC transformation mechanisms.

Method	Core idea	Advantages	Limitations
Field observations	Characterize atmospheric responses during heatwave events using observations.	• Direct atmospheric evidence; • Captures complex ambient conditions.	• Difficult to isolate temperature effects; • Limited observations of radicals and S/IVOCs.
Smog chamber and reactor experiments	Isolate temperature effects on VOC oxidation and SOA formation.	• Independent control of key variables; • Mechanism-focused experiments; • Direct quantification of temperature effects.	• Simplified atmospheric composition; • Difficult extrapolation to real heatwaves.
Box models and process models	Resolve VOC oxidation pathways and radical chemistry under constrained conditions.	• Detailed chemical-process resolution; • Mechanistic interpretation; • Process-level sensitivity analysis.	• Simplified physical environment; • Limited spatial representation; • Uncertainties in temperature-sensitive mechanisms.
Chemical transport models	Simulate regional impacts by coupling emissions, chemistry, and transport.	• Regional-scale assessment; • Emission-chemistry-transport coupling; • Process attribution through sensitivity simulations.	• Dependence on emission inventories; • Uncertainty in temperature-dependent parameterizations; • High computational demand.

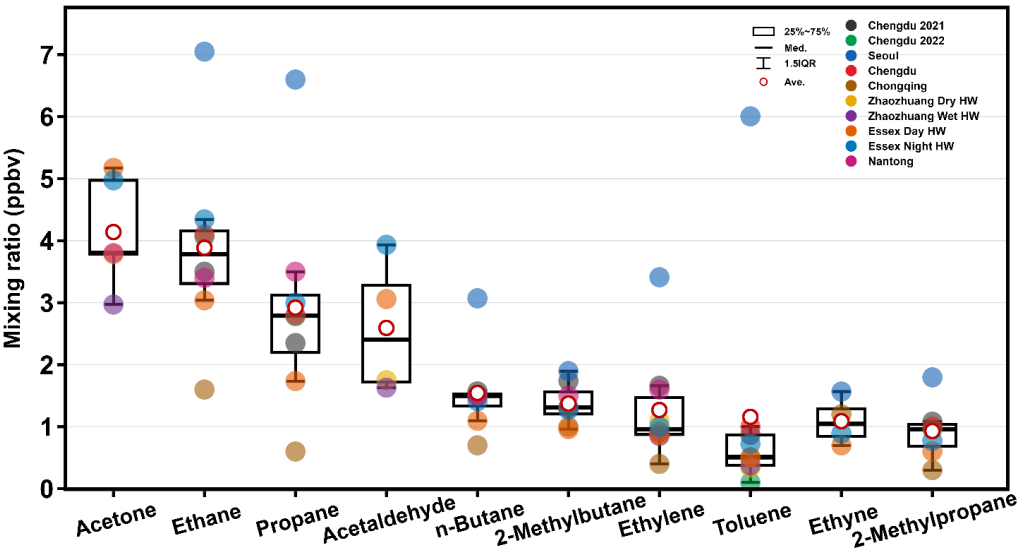


Figure 1. The average mixing ratios and percentages of major ambient VOC species during heatwave (HW) events. Data of Chengdu 2021 and 2022 is obtained from Kong et al. (2025); data of Seoul is obtained from Gil et al. (2026); data of Chengdu and Chongqing is acquired from Wang et al. (2024d); data of Zhaozhuang is obtained from Wang et al. (2026a); data of Essex is obtained from Lee et al. (2006); and data of Nantong is obtained from Chu et al. (2022).

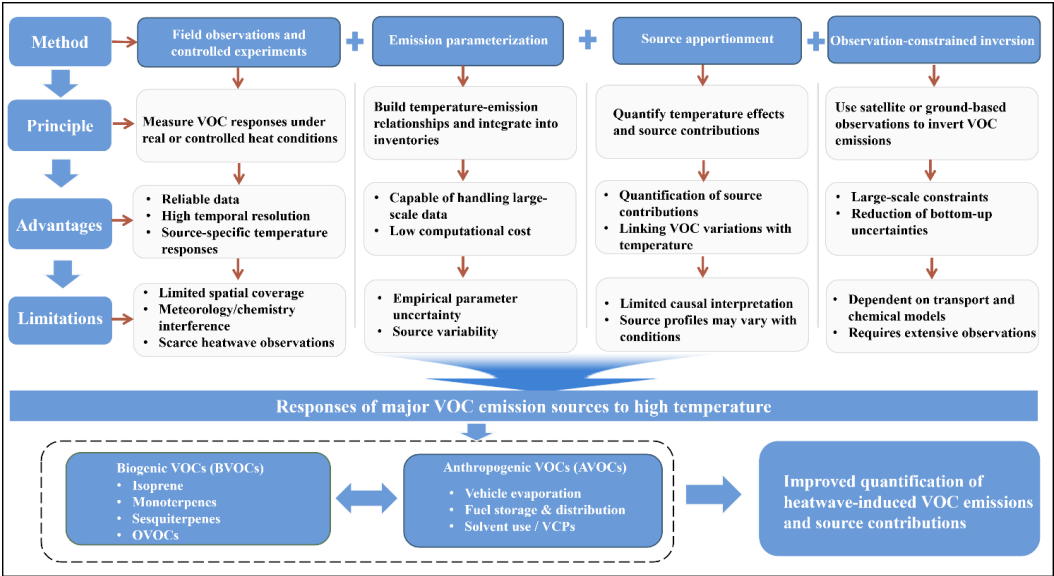


Figure 2 The methods for quantifying temperature-dependent VOC emissions and their responses.

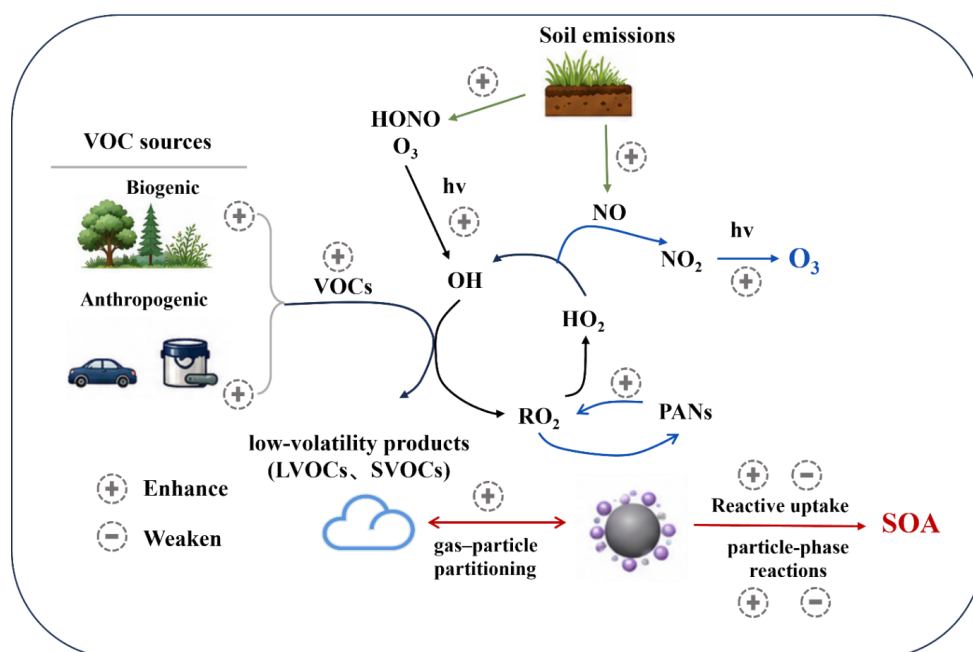


Figure 3. Schematic illustration of heatwave effects on the atmospheric transformation of VOCs into O_3 and SOA.