A PLAIN-LANGUAGE RESEARCH STORY

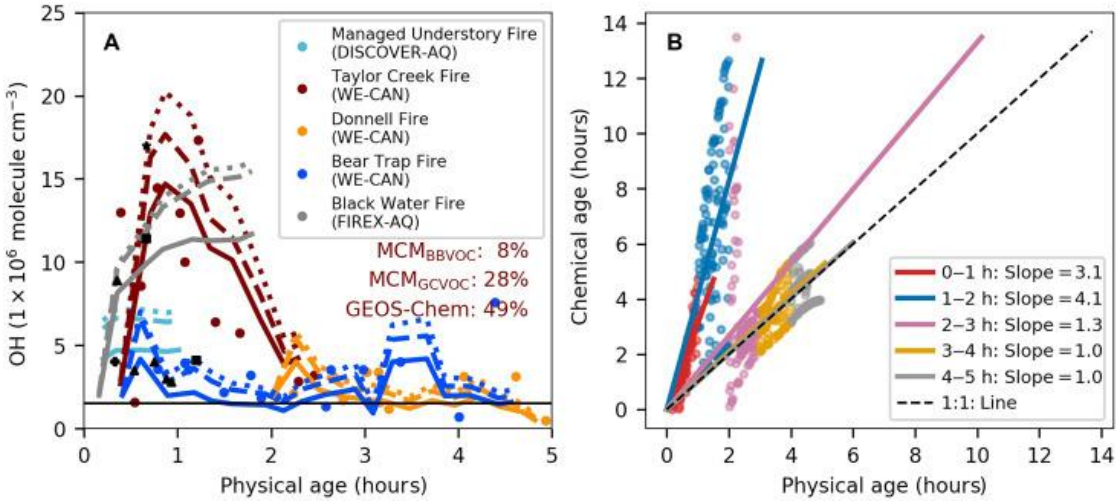
Wildfire Smoke Chemistry Runs in Fast-Forward

Aircraft observations reveal unusually rapid chemistry during the first two hours after emission

Jin et al. (2026) | Science Advances

Wildfire smoke does not carry a clock, but its chemistry does. In the five selected daytime plumes, the first two hours unfolded in fast-forward: after one hour of travel, the smoke had experienced about as much oxidation as it would in three to four hours under typical background conditions. We used observations from three major US aircraft campaigns. The aircraft crossed each plume near the fire and again farther downwind, giving us snapshots of how the plume-center chemistry changed during the first five hours after emission. To compare the plumes fairly, we separated travel time from chemical age. Travel time described how long the smoke had been moving downwind. Chemical age described how much oxidation it had experienced. During the first two hours, chemical age raced ahead. What powered this early burst of chemistry, and what did it produce?

During the first two hours, each hour of travel packed in roughly three to four hours' worth of oxidation under typical background conditions.



OH was highest during the first one to two hours, when chemical age advanced much faster than physical age.

Figure note: Physical age was estimated from the distance from the fire and wind speed measured by the aircraft. We calculated chemical age by dividing modeled OH exposure by a typical ambient OH concentration of 1.5 × 10^6 molecules cm^{-3}. This converts the plume's oxidation history into an equivalent time; it is not its actual travel time. OH was inferred from VOC–CO chemical clocks and observation-constrained modeling rather than measured directly.

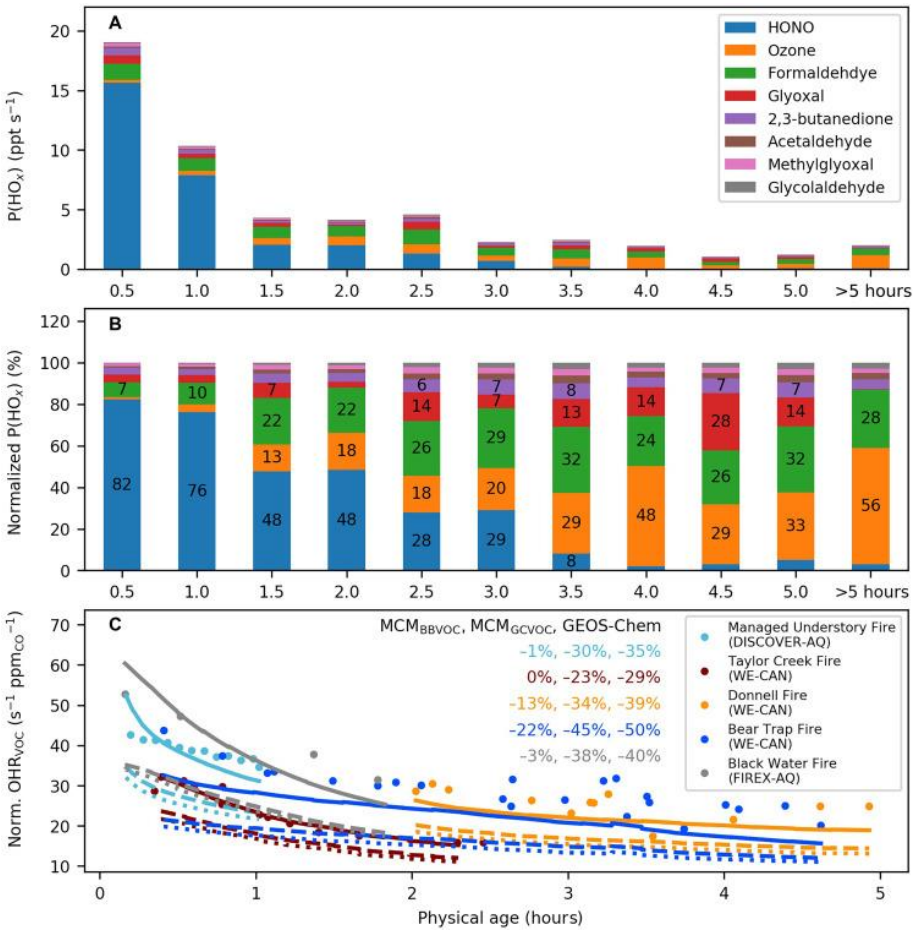
A CHANGING RADICAL SOURCE

What Drove the Smoke's Rapid Chemistry?

The source of reactive radicals changed as the smoke aged.

OH acts like the atmosphere's cleaning crew, but its reactions do more than remove gases. They also start the chemical chains that reshape a smoke plume. During the first hour, we found that most of the radicals driving these chains came from HONO breaking apart in sunlight. Averaged across the five plumes, HONO accounted for about three-quarters of the estimated radical production. One especially HONO-rich plume pulled that average upward.

HONO did not last. As it disappeared, oxygenated organic gases became more important. Between two and five hours, sunlight breaking apart these gases supplied roughly 40%–60% of the estimated radical production. As the smoke grew older and more dilute, ozone breakdown in sunlight supplied a larger share of the radicals. Our observation-constrained OH estimates were highest during the first one to two hours—about 5–20 million molecules cm^{-3}—before falling toward typical background levels after roughly three to five hours.



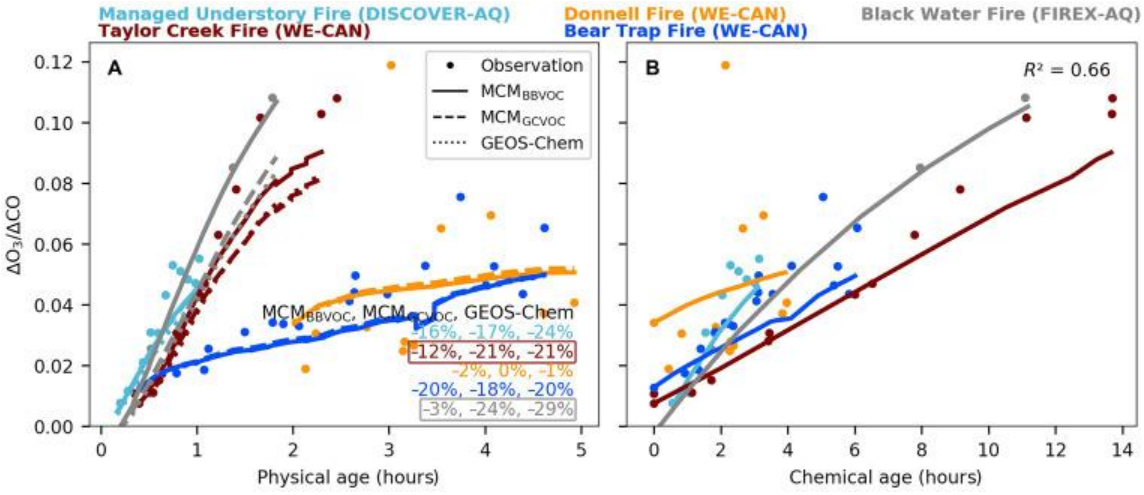
HONO dominated the radical source early. Oxygenated organic gases and ozone became more important as the smoke aged.
Jin et al. (2026), Fig. 2, CC BY 4.0.

This early burst of OH also helped drive rapid ozone formation.

CHEMICAL AGE EXPLAINS THE DIFFERENCE

Why Did the Plumes Make Ozone at Different Rates?

Chemical age explained much of the difference among the five plumes.



Ozone changes lined up more clearly with chemical age than with travel time.
Jin et al. (2026), Fig. 3, CC BY 4.0.

Ozone formed rapidly in all five plumes during the first five hours after emission, but its production rate still varied by a factor of four. Travel time alone did little to explain why.

An hour of travel did not mean the same amount of chemistry in every plume because each plume accumulated a different OH exposure. Chemical age gave all five plumes a common oxidation scale. On that scale, ozone followed a much clearer progression: chemical age explained about two-thirds of the variation in ozone enhancement (R^2 = 0.66). Across VOC loss and the formation of ozone and PAN, it explained roughly 40%–70% of the differences among plumes and cut the spread in estimated rates from about fourfold to about twofold.

Chemical age showed how far ozone chemistry had progressed. It did not reveal whether VOCs or NO_x had the stronger control over ozone production.

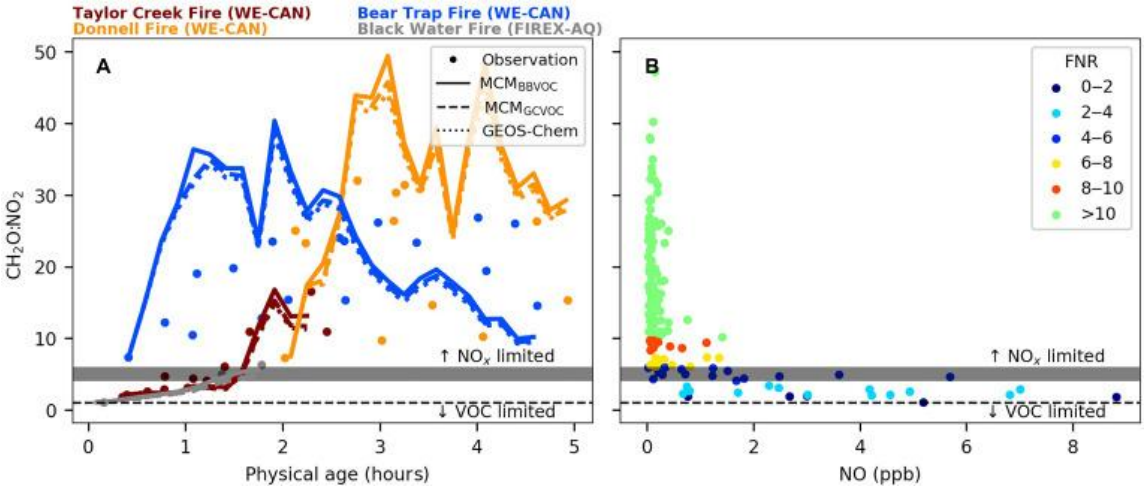
A CHANGING OZONE REGIME

Fresh Smoke Can Shift from VOC-Limited to NO_x-Limited Conditions

In at least two plumes, the chemistry controlling ozone production changed within the first two hours.

Ozone forms when VOCs and NO_x react in sunlight. Depending on the mixture, adding VOCs or adding NO_x can have the stronger effect. In at least two of the five plumes, ozone production began under VOC-limited or transitional conditions. As the smoke aged, the plumes moved toward NO_x-limited conditions during their first two hours, consistent with rapid NO_x loss.

A diagnostic built for urban pollution can miss this shift. Scientists often use the HCHO-to-NO_2 ratio (FNR) to gauge whether ozone production is more sensitive to VOCs or NO_x. A threshold near 1 is common in urban air. Applied directly to these smoke plumes, it would classify all five as NO_x-limited from the beginning and miss the earlier VOC-limited or transitional stage. For these five plumes, three statistical methods placed the transition around FNR values of 4–6. Two other chemical indicators pointed to the same change.



At least two plumes shifted from VOC-limited or transitional conditions toward NO_x-limited conditions as the smoke aged.
Jin et al. (2026), Fig. 4, CC BY 4.0.

Caveat: The FNR range of 4–6 is an approximate indicator derived from five selected plumes. It is not a universal threshold for all biomass-burning smoke.

That rapid change raises a practical question: can simplified models keep up?

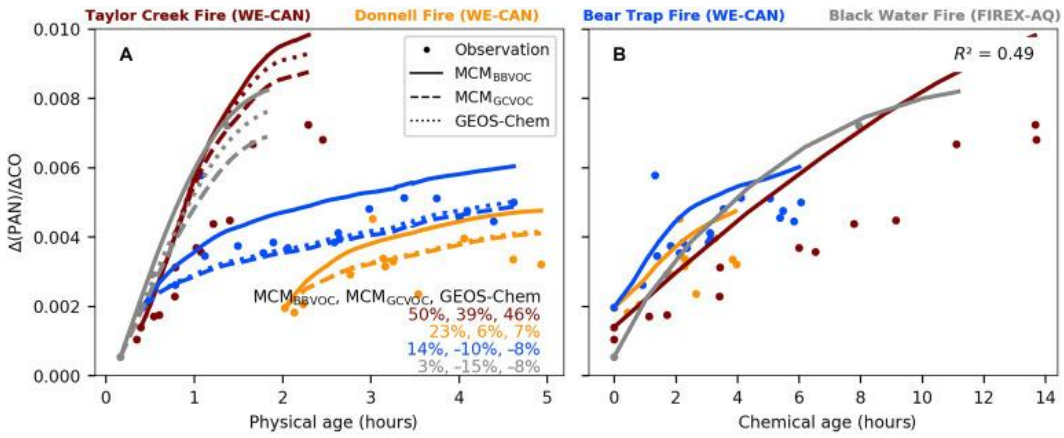
TESTING THE MODELS

How Well Did the Models Reproduce the Plume Chemistry?

The models performed best when they included a fuller mix of wildfire VOCs.

Our most detailed setup used measured HONO, observation-based sunlight conditions, and about 90 smoke-related VOC signals drawn mainly from the aircraft measurements. With this chemical detail, the Master Chemical Mechanism generally reproduced the radical budget and several key products within about 20%, although modeled OH differed by up to about 40% in some plumes. At the sampled plume centers, this observation-based setup captured much of the inferred OH and observed ozone behavior. Within that tightly constrained framework, we found no evidence of a major gap in current gas-phase chemistry.

When we gave the models a shorter VOC list, they performed less well. Modeled OH was up to about 50% too high. Ozone was 20%–30% too low in two VOC-limited plumes, and modeled organic nitrates were about 50% too low in three WE-CAN plumes. Acrolein, 1,3-butadiene, and furanoids accounted for about three-quarters of the missing VOC reactivity toward OH. Diacetyl and catechol also affected ozone or organic-nitrate chemistry. Even our detailed setup overestimated PAN—a molecule that can carry reactive nitrogen downwind—by about 50%–60% in one of four plumes, suggesting that some NO_x loss pathways remain underrepresented.



Chemical age explained about half of the differences in PAN production among plumes. Even the detailed model overestimated PAN in one of four plumes.

Figure shown: Jin et al. (2026), Fig. 6; model-comparison values also draw on Figs. 1, 3, and S6. CC BY 4.0.

Simplified mechanisms need a fuller representation of wildfire-smoke VOCs to reproduce OH, ozone, and organic nitrates.

Explore the study: Science Advances article · Supplement · NASA campaign data · F0AM box model

We examined five selected daytime US smoke plumes, focusing mainly on their centers during the first five hours. Physical age and OH were estimated rather than measured directly, and chemical age was calculated from modeled OH exposure. Some VOC and organic-nitrate signals were not calibrated to absolute concentrations. These five cases do not represent every wildfire plume or a national average.