Communicating Research to the General Public

The WISL Award for Communicating PhD Research to the Public launched in 2010, and since then over 100 Ph.D. degree recipients have successfully included a chapter in their Ph.D. thesis communicating their research to non-specialists. The goal is to explain the candidate's scholarly research and its significance—as well as their excitement for and journey through their area of study—to a wider audience that includes family members, friends, civic groups, newspaper reporters, program officers at appropriate funding agencies, state legislators, and members of the U.S. Congress.

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The dual mission of the Wisconsin Initiative for Science Literacy is to promote literacy in science, mathematics and technology among the general public and to attract future generations to careers in research, teaching and public service.

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Sources and Fates of Trace Gases and Aerosols in the Midwest United States

By

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A dissertation submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

(Chemistry)

at the

UNIVERSITY OF WISCONSIN-MADISON

2026

Date of final oral examination: April 9, 2026

Chapter 5. Atmospheric Chemistry for Non-Scientists

5.1 Science shouldn't be just for scientists

A common stereotype of scientists is that we sit in an "ivory tower", meaning we are either unwilling or unable to communicate our work in a way that is understandable to a broader audience. As someone who has lived in academia her entire life, I could not agree more. Even when connecting with fellow scientists, that communication is often hindered by our need to use convoluted language that makes us seem intelligent- I have been guilty of this too. Jargon has a time and place for quick communication amongst experts, but learning how to translate this to the 99% of the population that has never thought or cared about our work is a critical skill largely missing from our training as scientists. *Note to the reader: I am about to immediately contradict myself by saying that some jargon is unavoidable. Therefore, I have included a glossary at the end of this chapter (Section 5.7) with some of the jargon-y words and terms I use that I encourage you to reference if you get lost. I also include many citations throughout this chapter, which are either references to support my claims and/or resources to learn more about something I talk about.*

The University of Wisconsin, Madison is a land-grant university, meaning part of our research mission is to serve our community. This lack of effective communication, humility, and understanding from scientists constitutes a major failure in this regard. Without a bridge between researchers and non-scientists, we doom ourselves to a future of scientific misinterpretation, misinformation, and distrust, with widespread implications for day-to-day lives and policy.

This was demonstrated perfectly during the COVID-19 pandemic, when science, a naturally slow and iterative process, could not keep up with the policy decisions made around it. The result was policy made on the "best available science", which at the time had not gone through the rigorous peer review process it normally would. Because of this rapid timeline, decisions were made with unearned confidence that dramatically impacted the lives of all. When these precautions were repealed by policymakers as the science progressed, society became wary of scientists because the scientific process was not well communicated.

Science and technology are evolving at a rate never before seen, with broad impacts to scientists and non-scientists alike. An open, honest, and respectful dialogue between the research community and the rest of the world is more critical than ever to rebuild that trust. I write this chapter in the hopes of opening that dialogue, demonstrating the necessary humanity of the scientific process, and showing that science is not just for scientists. I would also like to acknowledge Professor Bassam Shakhashiri's work in creating the Wisconsin Initiative for Science Literacy program, which has advanced all of those goals long before this chapter was written. Finally, I would like to thank Elizabeth Reynolds and Cayce Osborne for their help bringing this chapter to life. Although the work I describe in this thesis is merely a drop of the bucket of science happening today, I hope that this chapter can crumble a bit of that scientific ivory tower.

5.2 Why I care about air quality, and why you should too

It can sometimes be difficult to explain to people why they should care about air quality. We naturally care about the quality of our water and food because we've trained our bodies to identify when something just seems *wrong*, like smelling when meat has gone bad or noticing your water is off-colored. If we miss these warning signs before ingestion, it's usually obvious pretty quickly when we eat or drink something that doesn't agree with us. On the other hand, it typically isn't immediately obvious to most when they are breathing poor air. We generally haven't trained our senses in the same way to identify poor air quality, and its health effects aren't always immediate or clearly linked like the stomach bug you get after eating undercooked chicken. It can be hard even for me, who has thought about air quality for years, to convince myself that out of sight should *not* always mean out of mind.

There are some ways that we can assess air quality using our bodies, though. For example, the smoke from wildfires can be detected by sight (and sometimes smell) even after it's travelled thousands of miles away from its source[1] (**Figure 5.1**). The haze you might see during one such event is made of aerosols, or tiny bits of liquid and/or solid suspended in the air. Although the actual composition of the aerosols are different, this is similar to a hazy skyline you might see on a poor air quality day in a big city. These aerosols infiltrate your body when you breathe, and depending on their sizes, they can even be absorbed into your blood from your lungs[2]. This can cause a variety of health issues, with the most common being asthma[3]. The contents in aerosols can also be biologically concerning, which is why masks became crucial to slowing the spread of COVID-19, for example[4,5].

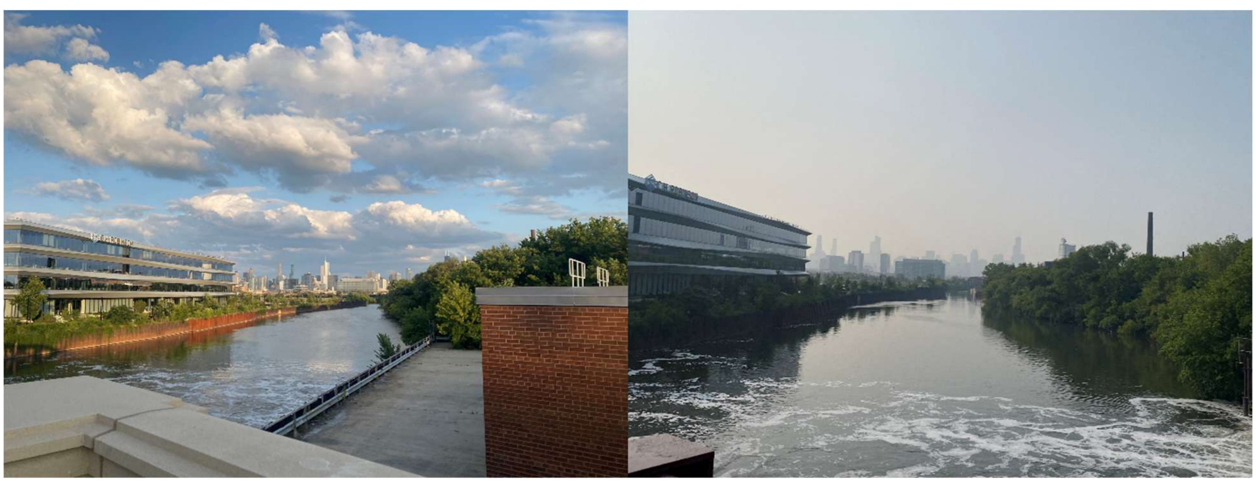

Figure 5.1: Low aerosol (left, July 20 2023) and high wildfire aerosol (right, July 25 2023) days in Chicago, IL

You can also smell the gaseous chemicals in the air that may be affecting air quality, though this can be much less obvious. Sometimes these chemicals can have an unpleasant odor; for example, benzene is a molecule that is mostly responsible for the smell of gasoline. Unfortunately for those of you who love that smell, benzene itself is a carcinogen (i.e., a substance that can cause cancer), and it undergoes chemical reactions in the air that make it a precursor to pollutants measured by the US Environmental Protection Agency (EPA) like ozone and aerosols[6]. Other chemicals have more pleasant odors. For example, when you light a candle, use shampoo, or put on lotion, the scents are likely from a type of chemical called a monoterpene. Don't worry, these are generally safe for humans to sniff. However, they are very quick to react with other chemicals in the air and, similarly to benzene, go on to readily generate ozone and aerosols[7].

In addition to human health, what is in the air is also important in terms of climate. Everything that gets emitted into the air has to go somewhere. As I already mentioned, gases can react in the air to form aerosols. Those aerosols, as well as aerosols directly emitted from events like wildfires and waves breaking in the ocean, can act as seeds for clouds to form. They can also modulate the amount of precipitation released from clouds, as well as their net warming and cooling effects on the climate[8,9]. We see this clearly every day in the form of contrails from planes (**Figure 5.2**). Contrails occur when the upper atmosphere is cold and humid, allowing water vapor to condense onto aerosols emitted from the plane[10]. While I'm on the subject, these contrails are a normal consequence of burning fuel in the upper atmosphere; if we could drive cars around at that altitude, they would do the same!


Figure 5.2: Contrail from an airplane[46]

Finally, air quality has important economic implications. Poor air quality can lead to a variety of negative health impacts, with the worst of those typically disproportionately felt by low-income and ethnic-minority communities, for example due to their proximity to oil distilleries, power plants, and high-traffic roadways[11–13]. People who spend a lot of their time in areas of poor air quality, especially children, can expect higher risks of asthma and other chronic respiratory diseases, cardiovascular disease, lung cancer, stroke, neurological and reproductive system disorders, and mortality[14]. These health consequences generate considerable economic burdens: healthcare expenses increase and worker productivity decreases[15–17]. A reduction in recreation and tourism associated with poor air quality also hurts the economy[18]. This can include tourists and locals avoiding beaches that are stinky due to a bloom of algae, or a city whose skyline has disappeared due to smog or wildfire aerosol. Furthermore, pollutants like ozone can impact agriculture by reducing crop yield[19].

All of this is to hopefully give a little more context regarding the importance of air quality, as well as inform you of ways you can assess air quality without fancy instruments (though your weather app is always a good way to double check for alerts!). However, I understand that a scientist spouting information isn't always the most inspiring. Because of this, I'd like to briefly explain why I have spent so many years earning a Ph.D. in this area.

I grew up around a mixture of small, industrial cities and rural farmland. Once I was old enough to hold a water hose, I was tasked with cleaning the back patio. We lived right down the road from a coke plant and steel manufacturer, which resulted in a fine layer of dust on all of our patio furniture that had to be cleaned every week or so. As a child, I was just annoyed by another chore; as I grew older, however, I became curious of what is in that dust that we inhale before it settles. I now know that dust likely contained a mixture of carcinogenic chemicals that I study today, as well as heavy metals. To escape this polluted air, my family would often go camping near a lake (can you tell I'm from the Midwest?). Around my teenage years, though, I recall the lakes getting stinkier, and eventually being told no one was allowed in the water because of a bloom of toxin-producing algae. When I began researching water quality as an undergraduate student, I learned that these are called Harmful Algal Blooms (HABs), and are often caused by excess nutrients from agricultural runoff[20].

A friend from college once visited my hometown and remarked, “the diminutive Ohioan was born among the corn, but ye amid pillars of smoke. lo, a lake of fire erupteth.” He was an English major, if you couldn’t tell, and the famous fire-catching Cuyahoga River is in *northern* Ohio, but you get the point. As a child, I witnessed first-hand how humans can impact the environment, and how the environment can impact us, inspiring me to pursue a career in policy-relevant environmental science. I’ll end this section with a quote I heard as a young graduate student that has stuck with me: “you can choose the food you eat and the water you drink, but not the air you breathe”. A bit simplistic of a viewpoint, but it has helped me, as I hope it will help you, realize working towards cleaner air is a benefit for *everyone*.

5.3 What does an atmospheric chemist do?

Similar to a stool, there are three pillars to atmospheric science: lab work, field measurements, and modelling. An atmospheric scientist might do all three themselves, or they may work as part of a large, collaborative team. For example, I took one of our instruments to Chicago to measure ambient gases during the summer, which would be the field work portion. Field work usually generates a massive amount of data to process and analyze; let’s say for this example, someone discovered a new, interesting molecule. They could transition to a laboratory to study that molecule in a controlled environment. They might discover how this molecule can chemically react with other molecules in the air, forming new molecules that react chemically, continuing the cycle. That new chemical reactivity data could be passed on to a modeler, who integrates it into their modelling framework. That model could then more accurately predict things like air quality. The modeler might then require more information on a different molecule, motivating more field work. As with any scientific discipline, it's a highly iterative process to get to publishable results (**Figure 5.3**).

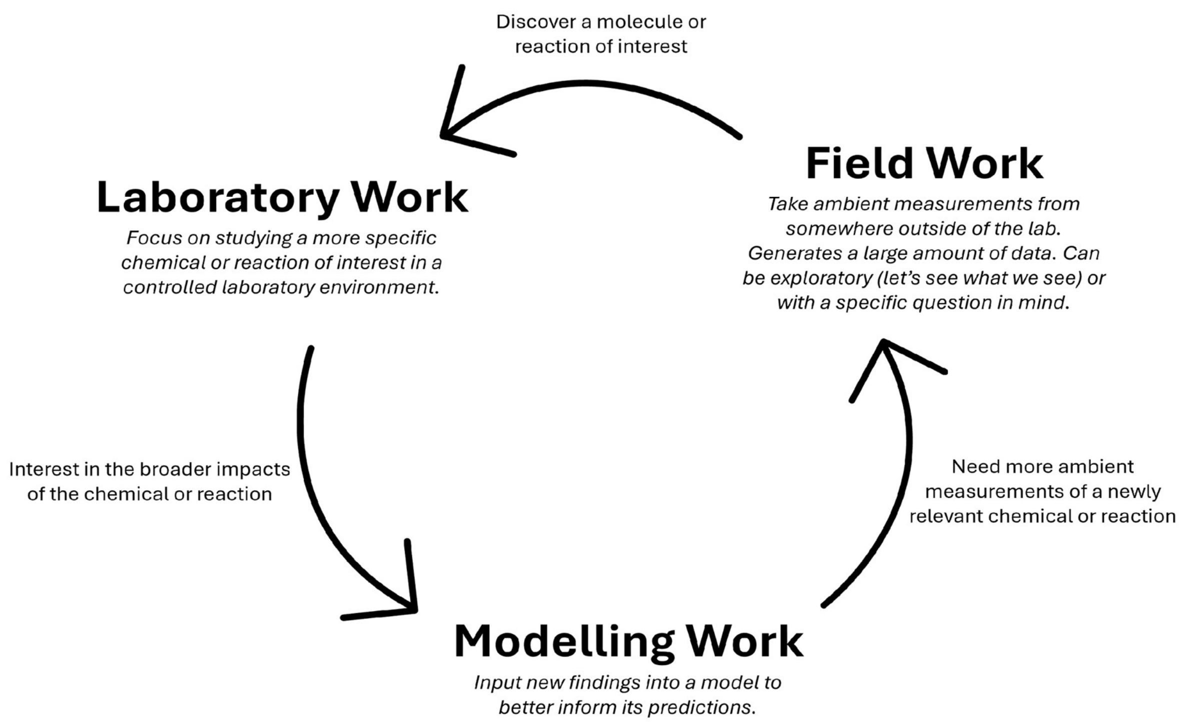

Figure 5.3: Example interface between field, laboratory, and modeling work

A major portion of my work as a graduate student has been based on the field measurements I took in Chicago during the summer of 2023. As an undergraduate, my field samples were water and sediment- things I could see and feel. Studying what is in the air and its chemistry was an entirely new world. Suddenly, I was trusting instrumentation to measure gases that were at concentrations in the air so small I had no way of detecting them with my own senses.

Take isoprene, for example. Isoprene is an organic (carbon-based) molecule that exists as a gas in the atmosphere (a Volatile Organic Compound, or VOC) with the molecular formula of C_5H_8, meaning it has five carbon atoms and eight hydrogen atoms. The average concentration of isoprene that I measured in Chicago was 47 Parts Per Trillion (ppt), meaning there were 47 molecules of isoprene for every 1,000,000,000,000 molecules in the air. A useful way to visualize this unit is if we think about time. One trillion seconds is equal to 32,000 years; in our case, 47 seconds out of 32,000 years! Alternatively, a haystack containing one trillion pieces of hay would be about the height of a 24-story building; now try finding 47 needles in a 24-story haystack. Although I had used this instrument before I took it to Chicago, it still took a lot to convince myself that this big box of metal and electronics could actually measure something that dilute.

The day-to-day of field work in graduate school was another jarring transition. As an undergraduate I collected samples once a week, at most. As a graduate student, field work was a "campaign", or high-intensity periods of data collection. Gases are emitted into the air from a near-infinite variety of sources, where they can then react or simply be moved away by the wind. The exact composition of the air you're breathing at this very moment won't happen again; this is why our instruments need to be measuring constantly (one measurement of over 900 molecules every second, in my case). And if our instruments are constantly measuring, we need to be constantly monitoring our instrument.

Although one of the most rewarding times of my life, my time in Chicago was also very intense. The campaign began with us transporting hundreds of thousands of dollars of fragile instrumentation about 150 miles across state lines. After the instruments and sampling line were set up, I was in charge of collecting data for about six weeks from the building's rooftop (**Figure 5.4**). As the only person there monitoring the instrument, at times I was working over 100 hours per week, setting alarms throughout the night to wake up and make sure it was still operating properly. During this time, I was processing raw data, adjusting sampling plans informed by these results, performing maintenance on the system, and troubleshooting when the instrument decided it didn't want to work.

Figure 5.4: Transporting fragile equipment in a van with the generous help of the machine shop crew (left), setting up instruments in our collaborator's laboratory space in Chicago (middle), and sampling port of instrument on the rooftop (right)

As you might imagine, this portion of my Ph.D. gave way to a lot of emotions. Independently operating this instrument and generating high quality data was empowering. Knowing I could use this data to eventually inform air quality policy and advocate for solutions was gratifying. To be frank, though, it was also extremely stressful. Every second that the instrument wasn't operational was a second of data I would never get back.

There was one night that I stayed late to troubleshoot the instrument. I really wanted to make sure the instrument would be taking measurements that night, since I knew we were about to be hit by an air mass from the Canadian wildfires, and I really wanted that data. After hours of working on the instrument, I finally got it back online… only to forget to connect the instrument back up to the inlet sampling the outdoor air. Instead of sampling this once-in-a-lifetime air quality event, I was sampling indoor lab air, which now shows up as a big white block of missing data in all of my figures. That night still haunts my dreams… as well as the Airbnb I had booked for the

7 weeks I would be there that turned out to be a scam. What I am trying to convey is that, at the end of the day, scientists are humans too, and, despite our best efforts, do make mistakes (especially when incredibly sleep deprived).

5.4 Isoprene and monoterpenes in Chicago

After about seven weeks in Chicago, I returned to Madison to process and analyze my data. Because my campaign was "exploratory", meaning we didn't have a specific question or hypothesis going into data collection, this process took around a year. This timeline isn't unusual for a field campaign, especially since I alone was processing the data, but my perfectionism and tendency to go down rabbit holes definitely stretched the process. Amongst many lessons, perhaps the most important that I learned is that high quality, reliable data can't be rushed. After about a year of working up this data, I finally decided on a story to tell, inspired by some recent work in the community.

Historically, the most important source of VOCs in United States cities has been fuel burning from vehicles[21]. However, the modernization of vehicles and fuel efficiency has dramatically reduced the amount of VOCs (and other pollutants) released. Now, scientists are looking for other sources of urban pollution, and have found that volatile chemical products (such as cleaning solutions, soap, perfume, etc.) are an important source of VOCs in places like New York City and Los Angeles[21,22].

Some of the VOCs emitted from these products are called "terpenoids". Terpenoids are a broad group of molecules, best defined as isoprene (C_5H_8) and molecules built from isoprene units (e.g. monoterpenes and sesquiterpenes). Terpenoids react quickly with "atmospheric oxidants" (chemicals in the atmosphere that initiate a chemical reaction known as "oxidation"), especially in cities where these are relatively concentrated. Although terpenoids are at lower concentrations than VOCs from fuel burning, their quick reactions with these oxidants make them especially efficient as ozone and aerosol precursors (**Figure 5.5**).

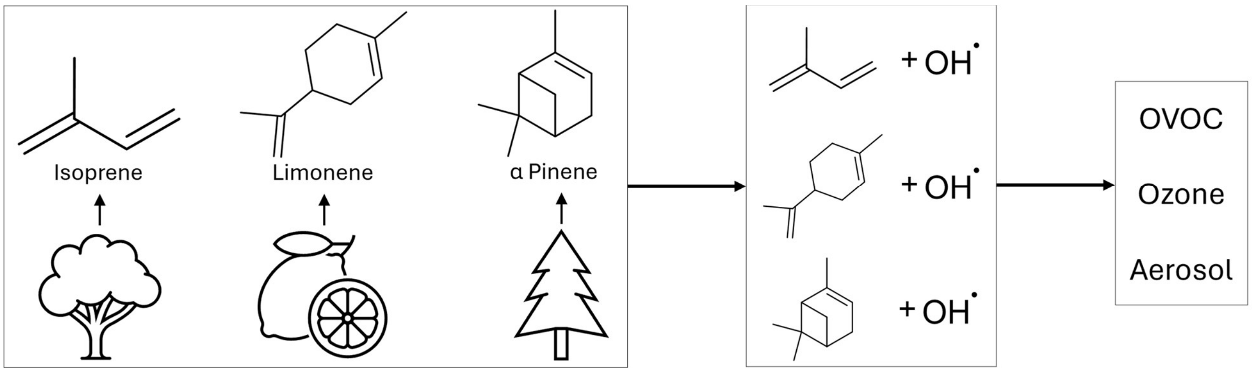

Figure 5.5: Plants emit isoprene and monoterpenes (left panel), which then quickly react with atmospheric oxidants like the hydroxyl radical (OH·, middle panel) to form oxygenated VOC (OVOC), ozone, and aerosol (right panel)

You're probably more familiar with terpenoids than you think. The reason oranges have that distinct smell is because they emit high concentrations of a monoterpene called limonene. The smell from pine trees is due to a monoterpene called alpha pinene. Eucalyptus gets its therapeutic smell from an oxygenated monoterpene called eucalyptol. The list goes on! Although these terpenoids are sourced from plants, humans will extract them and put them into things like scented lotions, perfumes, and cleaners, turning us into walking sources of terpenoids. This becomes important in big cities, where terpenoids from human sources play a larger role in air quality than we have historically thought. Understanding this is necessary to predict how changes in policy will affect air quality, especially in cities that have historically struggled to meet air quality standards set by the EPA, such as Chicago, Illinois.

To determine how much of these terpenoids are from humans (as opposed to plants), I utilized my data from Chicago[23]. There, I used two techniques called "mass spectrometry" and “gas chromatography”, both of which sampled and analyzed air from outside. Mass spectrometry is used to separate molecules by their masses and can measure hundreds of molecules every second. This data is useful to distinguish most molecules, and for its fast response time. However, molecules of the same exact mass (called “isomers”) can’t be distinguished with mass spectrometry. So, to separate my isomers, I use gas chromatography, which is a way to separate molecules of the same mass by some other chemical property, like how “sticky” it is to a given material[24].

I focus this project on monoterpenes, which are composed of two isoprene units ($C_{10}H_{16}$), with different spatial arrangements of the atoms making each monoterpene unique. I was able to isolate ten different monoterpene molecules and measure their concentrations in the air over the six weeks I sampled. Each monoterpene behaved differently in time, with some at their highest concentrations during the middle of the day, and others in the early morning (**Figure 5.6**). These daily trends for each monoterpene give us some idea about their sources. For example, the most abundant monoterpene, alpha pinene, had a daily cycle that was similar to decamethylcyclopentasiloxane, a chemical added to personal care products. These peaked early in the morning, which could be consistent with people showering, getting ready for the day, and applying their lotion, shampoo, and perfume. On the other hand, sabinene (the third most abundant monoterpene) had a daily trend similar to isoprene, a biogenic (primarily plant-based) VOC. These trends thus suggest that alpha pinene is mostly emitted by human sources, while sabinene is not.

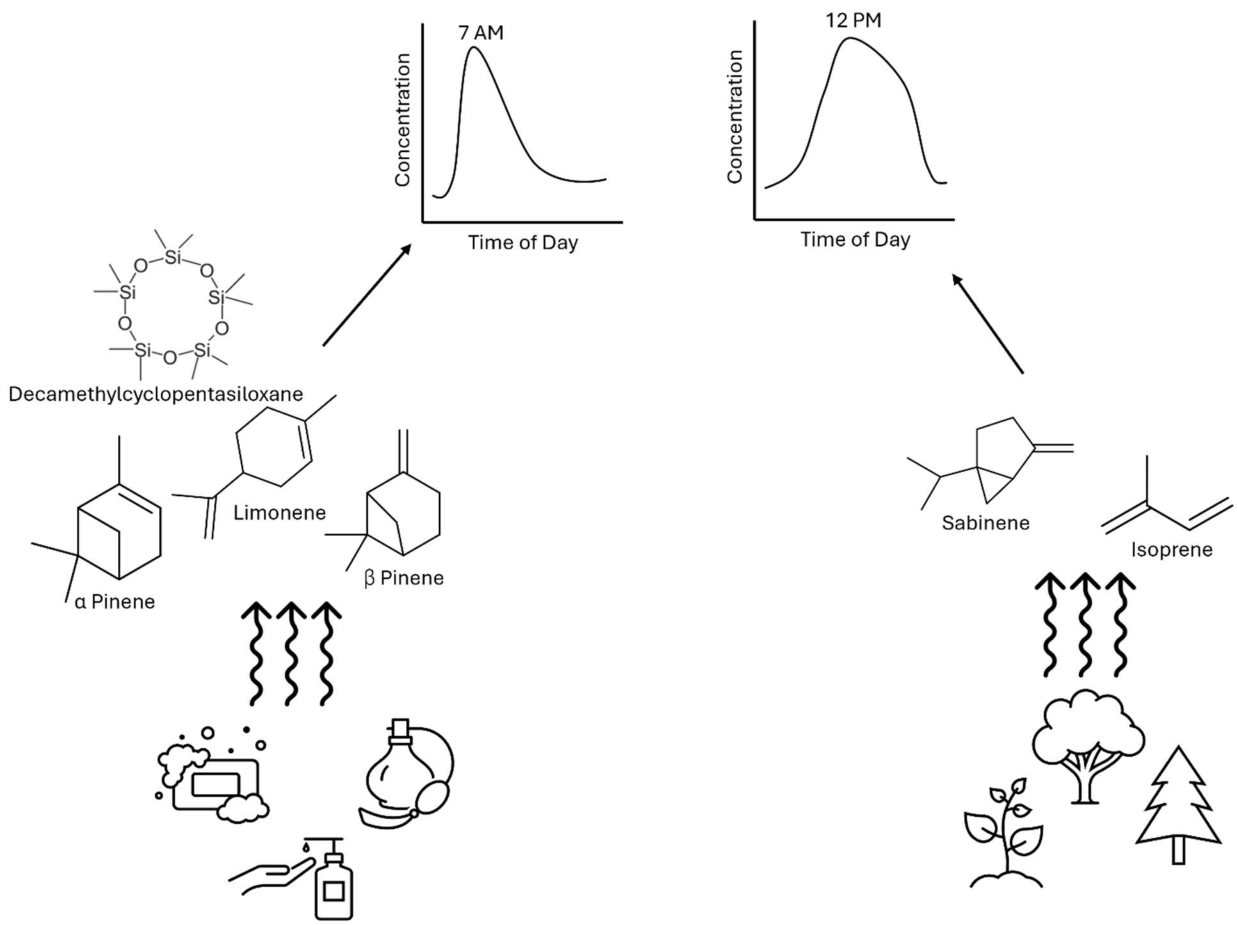

Figure 5.6: Some monoterpenes peak at the same time of day as decamethylcyclopentasiloxane, whose only source is from man-made products like lotion (left). Other monoterpenes, like sabinene, peak at the same time of day as isoprene, which is known to come from plants (right)

I used two methods to identify an actual number on the amount of monoterpenes from human sources. First, I used a statistical method called Positive Matrix Factorization (PMF). PMF essentially recognizes patterns in how different VOCs vary over time together[25]. In my dataset, it found that most of the monoterpenes I measured had a mixture of human and plant sources, based on similarities with how isoprene and decamethylcyclopentasiloxane behaved. By adding up the human contributions for all of my monoterpenes, I was able to conclude that at least 52% of the monoterpenes I measured were from human emissions. Compared to our previous estimate of 0%, this is a pretty big difference!

For more confidence, I verified this result with a second method, in which I assumed limonene to have zero biogenic sources in Chicago (not a lot of orange trees in the windy city!). In other words, Chicago limonene was exclusively emitted from humans. Using measurements from other papers of limonene concentrations in human environments, as well as my measurements of limonene concentrations in Chicago, I was able to estimate that between 46% and 59% of monoterpenes in Chicago are from humans, which agrees well with our initial estimate of 52%!

Although I have shown that around half of the monoterpenes in Chicago are from humans, one can still argue that their relatively low concentrations, especially compared to more commonly studied molecules such as those from fossil fuel burning, make this finding insignificant. For this reason, I compared their concentrations, as well as their reactivities with atmospheric oxidants, to these fossil fuel burning VOCs.

When considering all of these molecules together, terpenoids only account for 10% of the total concentration. However, of the three most important atmospheric oxidants, terpenoids account for 58% of reactivity with one (the hydroxyl radical, OH·) and over 99% of reactivity with the others (the nitrate radical, $NO_3\cdot$, and ozone, O_3) (**Figure 5.7**). In other words, if there are 100 $NO_3\cdot$ that have chemically reacted with this group of terpenoids and fossil fuel VOCs in one second, terpenoids reacted with

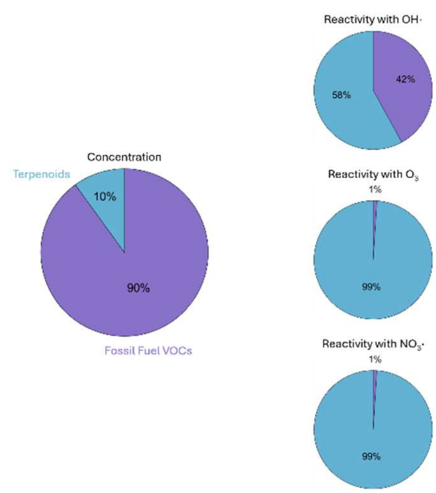

Figure 5.7: Concentration and reactivity pie charts for terpenoids (blue) and fossil fuel VOCs (purple)

99 of the $NO_3\cdot$ while fossil fuel VOCs only reacted with 1, even though there are many more fossil fuel VOCs.

When a VOC reacts with an atmospheric oxidant, this starts a chain of chemical and physical processes that eventually form pollutants like ozone and aerosols. This finding demonstrates that although they are at relatively low concentrations and are not necessarily a direct health concern like those from fossil fuel burning, they are very efficient precursors to much worse, EPA-monitored pollutants. Combined with the initial finding that roughly half of the monoterpenes I measured in Chicago are from humans, their efficiency as precursors for pollutants like ozone and aerosols makes for important policy implications.

Finally, I compiled similar measurements of terpenoids in different cities around the globe and demonstrated that the types and relative amounts of monoterpenes in Chicago are similar to the average urban distribution. This means that it is likely other cities globally are underestimating their anthropogenic monoterpene sources. To better understand air quality in these different cities and identify best policy practices to address urban air quality, scientists should aim to do similar studies in other major cities and in different seasons.

5.5 Closing remarks

I began this chapter by explaining my personal motivations for studying atmospheric chemistry, as well as outlining why the many consequences of air quality makes it one of many topics that non-scientists should care about. In the following section I attempted to give you a glimpse into the life of an atmospheric chemist, focusing on my favorite (and, at times, least favorite) part: field work. Although these few paragraphs don’t come anywhere close to fully capturing the life of a scientist, I hope it at least gave you an appreciation for the dedication scientists have for delivering high quality, meaningful, and exciting results. Finally, I described one of the projects I have completed as a graduate student. For a fully realized version of this story, I invite you to read Chapter 3 of my Thesis. Do be warned, however, that the way I wrote Chapter 3 is in the typical style of published academic work, which makes it a much denser and less accessible work. I finish this layman's chapter with a "frequently asked questions" section, with questions in no particular order. I was inspired to include this when, as I was writing this chapter, I recalled how difficult it was (and, sometimes, still is) for me to learn this field. I hope that the following will clear up some misconceptions and perhaps even help a fellow environmentalist who wants to learn about atmospheric chemistry but doesn't know where to start.

5.6 Frequently asked questions

What is the composition of the air?

Air is mostly made up of nitrogen (N_2, 78.084%), oxygen (O_2, 20.946%), argon (Ar, 0.934%), and carbon dioxide (CO_2, 0.042%). Although these four make up over 99.99% of all gases in our air, there are thousands of others that exist in "trace" (or very small) amounts[26]. Though low in abundance, these gases can have important implications for climate and air quality.

What is a Volatile Organic Compound (VOC)?

A VOC is a classification of trace gases in the air that are defined as organic (carbon-based) molecules that exist as gases at typical outdoor temperatures. For example, acetone (the primary ingredient in nail polish remover) is an organic molecule that, when left uncovered on a lab bench, will spontaneously turn into a gas over a relatively short amount of time.

What is an aerosol?

An aerosol is a tiny solid and/or liquid suspended in the air we breathe. Examples include hairspray, saliva, and smoke. We use two classifications to describe aerosols: their formation process, and their size. For their formation, aerosols can be designated as “primary” or “secondary”, meaning directly emitted into the atmosphere (like smoke) or generated through chemical processes in the air, respectively[27]. We also classify aerosols by sizes because smaller aerosols can penetrate deeper into our lungs and, when sufficiently small, can be absorbed into our blood stream. The two categories you’ll most often hear about is $PM_{2.5}$ and PM_{10}, where “PM” stands for particulate matter (another word for aerosol) and the numbers mean aerosols with diameters below 2.5 and 10 micrometers, respectively[28]. For reference, a human hair is about 60 micrometers in diameter.

Is ozone good or bad?

Ozone is a molecule which can absorb both ultraviolet radiation (from the sun) and infrared radiation (from the earth) and re-emit that energy. In the upper atmosphere (stratosphere), it is mostly absorbing ultraviolet radiation and emitting energy back into space. In the lower atmosphere (troposphere), it is mostly absorbing infrared radiation and emitting energy back towards earth, labelling it as a “greenhouse gas”[29]. The important comparison is the relative amount of energy emitted back into space versus earth. So, the short answer is that stratospheric ozone is good, while tropospheric ozone is bad. Furthermore, tropospheric ozone can react with other molecules found in high abundance at ground level, creating different greenhouse gases and pollutants.

What are the different types of air pollution?

The EPA monitors six "criteria air pollutants" whose outdoor atmospheric concentrations need to be measured to minimize adverse health impacts: ozone, particulate matter, carbon monoxide, lead, sulfur dioxide, and nitrogen dioxide. Ozone is formed by chemical reactions between VOCs and nitrogen oxides and can cause respiratory issues. Particulate matter, or aerosols, adversely affect your heart and lungs. Carbon monoxide is released through combustion and can lower oxygen levels in your bloodstream. Lead comes from a variety of sources including ore and metal processing plants and causes a number of health problems including neurological effects. Sulfur dioxide is emitted during fossil fuel burning and can cause respiratory issues, as well as act as a precursor to secondary aerosol. Finally, nitrogen dioxide is similarly emitted during fossil fuel burning and negatively impacts the respiratory system and acts as a precursor to both secondary aerosol and ozone. While this isn't an extensive list of everything that could be considered an atmospheric pollutant, these six pollutants are those deemed most important for monitoring and regulation. More information can be found on the EPA website[30].

How do we know climate change is caused by humans?

Although the earth has seen climates far different than that of our current one, there is abundant evidence from countless sources and methodologies that show that the current *rate* at which our climate is warming is ten times faster than the average[31]. Previous changes in climate were caused by small changes in the earth's orbit, resulting in more or less ultraviolet radiation from the sun hitting the earth[32]. However, this natural phenomenon cannot explain the current warming. Instead, the culprit is high concentrations of greenhouse gases, emitted by man[33]. For example, atmospheric concentrations of carbon dioxide, a greenhouse gas, are increasing 250 times faster than natural conditions would allow[31]. Carbon dioxide is a product of fossil fuel combustion, and by the 1950s, it became clear to a number of prominent scientists that the rapid industrialization following World War II was having a considerable impact on our planet (**Figure 5.8**). Of over 88,000 English-speaking peer-reviewed climate papers published between 2012 and 2020, only 28 (0.03%) were skeptical that man has caused this climate change[34]. These are not opinion pieces- rather, observable data that all point to one theory: climate change is caused by man.

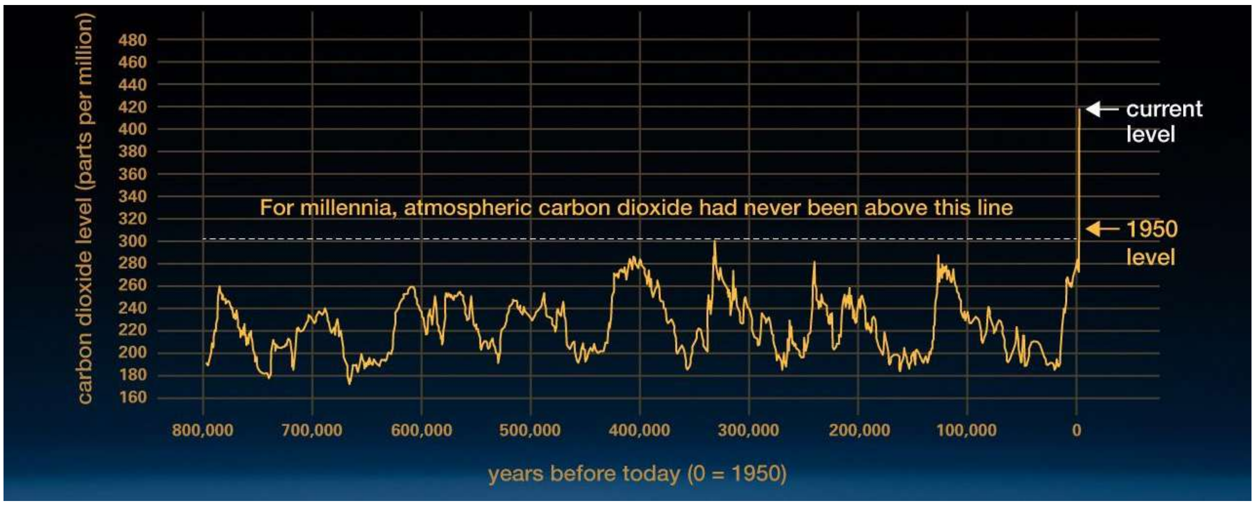

Figure 5.8: Carbon dioxide variability in the atmosphere over time[31]

Although we will face the consequences of our greenhouse gas emissions for centuries to come, action taken today to make our energy production "greener" will help avoid worsening the problem[35]. This would also result in better air quality and job growth[36]. If we continue on our path, however, we can expect higher temperatures, drought, more extreme natural disasters, and more[37].

How far can air pollution travel?

Gases and aerosols in the air all have different journeys, from where they are emitted to where they end up. Those journeys can take longer or shorter amounts of time. For example, some VOCs chemically react within seconds of being emitted into the atmosphere, while others can hang around for years[38]. Aerosols can also have variable lifetimes, from hours to weeks in the troposphere[39]. The longer the lifetime of something in the atmosphere, the more opportunity it has to be moved by wind. For example, Saharan dust can travel across the Atlantic Ocean all the way to Southeastern United States and beyond[40,41] (**Figure 5.9**). Gases can also traverse great distances before chemically reacting at a new location and generating pollution[42].

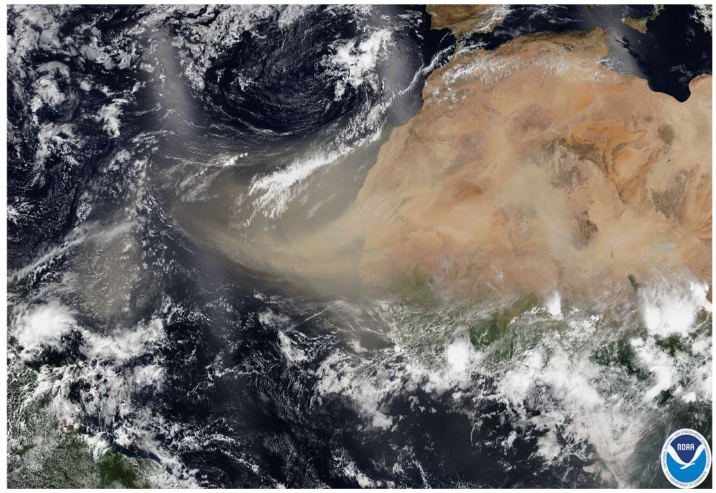

Figure 5.9: Saharan dust, as seen by the NOAA-20 satellite[47]

How does air pollution cause pretty sunsets?

The color of the sky, whether that is the bright blue of midday or vivid yellows and oranges of sunrises and sunsets, is due to the scattering of light by the gases and aerosols in the atmosphere. When the sun is directly overhead, we expect to see a bright blue sky, because that wavelength is most effectively scattered by the gases and aerosol in the atmosphere. However, when the sun is on the horizon, its light must travel a further distance. Over the course of this distance, that blue light is effectively scattered away, leaving us with the longer red, orange, and yellow wavelengths to observe. High concentrations of aerosol in the atmosphere, for example during a wildfire event, exacerbate this effect, leading to even more vivid sunrises and sunsets[43]. Although beautiful, these intense colors could indicate a high level of aerosols in the air, so be sure to wear a properly-fit mask while admiring the sky.

What is the research process?

The process can take many forms, but I'll talk about a general outline. First, you search the scientific literature on whatever topic you're interested in, then craft a research proposal that you submit for grant funding. Sometimes this is done by graduate students and post docs, but often it is a collaborative process led by principal investigators. If you're funded, begin conducting research. This can look very different for different projects, even in the same field, including lab, field, and desk work. But the common theme is that since your work should be novel in some aspect, this is the first time in the history of the world anyone is trying to answer the question you're asking using the methods you're using. Therefore, oftentimes this looks like a highly iterative "trial and error" process, informed as best as possible by cobbling together methods and ideas from existing literature. Hopefully, throughout this process you will learn something new that deserves publication. If that is the case, you analyze your data and write up your work. A publication should generally include a background, methods, results, discussion, and conclusion sections. You then choose the most relevant journal (many shoot for "high impact" journals) and submit your manuscript. Your manuscript is then assessed by a number of other experts in the field, and is either rejected, accepted with revisions (most common), or accepted. If your work needs revisions, you may go back and forth with the reviewers to perfect your manuscript before it is officially published. You can then use findings from this work and questions generated therein to write another research proposal for more funding.

What is "basic science"?

Basic science is scientific research done with no particular goal in mind or problem to address. Rather, it is an attempt to understand how the world works based on curiosity alone. Despite its name, basic science is not more or less inherently challenging than other types of scientific pursuits. It isn't always intuitive why time and money should be utilized for this kind of work as opposed to very solution-oriented work known as “applied science”. However, so many valuable advancements are thanks to findings from this type of work, as honored by the Golden Goose Award[44]. For example, federal funds were used to study growth hormones in laboratory rat pups- a project without a clear problem to solve. That federal (National Institute of Health) money funded a graduate student to stroke a tiny brush up and down the rat pups’ bodies. Inadvertently, those researchers discovered that separating the rat pups from their mothers inhibited growth hormones, which was reversed when the pups were stroked with the brush to mimic the mother’s grooming. The result was the implementation of infant massages for premature human babies, which has reduced the average NICU stay by six days, faster growth rates, and $4.7 billion in national healthcare savings[45]. Like so many other basic science projects, arguing why federal funding should be allocated towards rat massages is no easy task, but it can deliver enormous and unpredictable benefits.

How can this science have “real world” applications?

The science my research group does lends itself well to policy applications in particular. Because my work on terpenoids has important implications for air quality, especially as the distribution of VOCs continues to change, I have discussed these findings directly with Chicago policymakers. This better informs them where to focus change, and how those (not necessarily intuitive) changes can reduce the number of air quality exceedance events that frequently plague Chicago. For example, regulation on the amount of terpenoids used by manufacturers of personal care products and clear labeling of products could encourage manufacturers to better optimize their formulas and reduce terpenoid emissions. A better understanding of the types and natural sources of terpenoids as well as their impact on air quality could better inform what kinds of vegetation to plant and where. Inputting my data into local air quality models could better prepare citizens for poor air quality and teach them how to protect themselves.

5.7 Glossary

Aerosol: Small solids and/or liquids suspended in the air

Ambient: Surrounding air that has not been deliberately manipulated by the scientist

Carcinogen: A substance which has the capacity to cause cancer

EPA: Environmental Protection Agency

Instrument: A machine used in a scientific application to collect data

Isomers: Chemicals of the exact same mass

Isoprene: The earth's most abundant plant-based VOC (excluding methane)

Oxidant: A chemical capable of taking electrons away from another chemical

Smog: Air pollution caused by man, composed of ozone and aerosols

Terpenoid: Chemicals made up of two or more isoprene units, including monoterpenes

Troposphere: The lowest part of the atmosphere, where humans live

VOC: Volatile Organic Compound

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