Recommendations for the future of the air quality ecosystem in California

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Table of Contents

Introduction

Air is a mixture of chemicals. Chemicals are added and removed from the atmosphere by the biosphere and human activity. For example, photosynthesis is a process that adds oxygen (O_2) to the atmosphere and removes carbon dioxide (CO_2). Soil microorganisms metabolizing nitrogen in natural and fertilized ecosystems release nitric oxide (NO). On a global scale, a similar amount of isoprene—an extremely reactive organic chemical—is emitted to the atmosphere from plants as the total emissions of all other organic molecules emitted by human activity (Ehhalt et al., 2001). As emissions from human activity decrease, isoprene and other emissions are becoming important even in cities such as Los Angeles (LA).

Many types of emissions are a result of combustion of biomass and fossil fuels. Emissions can occur prior to combustion, for example evaporative emissions from gasoline vehicles or methane (CH_4) leaks from oil and gas drilling, transmission, and post-meter pipes and valves. Anthropogenic CO_2 emissions from fossil fuel combustion have profound effects on our climate. Emissions of nitrogen oxides ($NO_x = NO + NO_2$) and particulate matter (PM) from fossil-fuel-based transportation and electric power generation greatly affect the composition of air. Volatile organic compounds (VOCs) released from transportation, industry, and from chemicals used in our homes also matter. These emissions, the atmospheric chemistry that occurs afterward, and the eventual removal from the atmosphere vary widely in time and space. For example, emissions of large particles from vehicle braking systems predominantly occur along highways; since the particles are large, they are removed by depositing to surfaces within ~300 meters and within hundreds of seconds from the location and time of the emissions (Staffelini & Gialanella, 2021). In contrast, CO_2 emissions are also highly localized but the removal is not. CO_2 is removed by uptake to the oceans and biosphere across the whole planet and on time scales of ~100–1000 years (Joos et al., 2013). The removal timeline is important for many reasons. Particularly considering that many chemicals in the air contribute to poor health, we are especially concerned about the uneven spatial patterns of such emissions, and the bias for the emissions to occur in underserved, low-income communities with high cumulative environmental and health burdens (Apte et al., 2019).

This is just a brief and partial description of the chemicals and processes that affect the air. Our understanding derives from a history of observations, research, policy design and implementation, and community engagement. In this document, we outline recommendations for the State of California as it begins to consider the next generation of an air information system. Our goal is to frame a discussion of possible investments that will lead to:

- a more accessible and transparent system for observing and communicating about chemicals in the air, where those chemicals are emitted, and which areas and populations they impact
- an observing system that attends to both the need to maintain accurate records of multi-year trends that can be subtle while also mapping large variations that occur between communities today
- a system for democratizing assessment, prediction, and communication about patterns of chemicals in the air, and how plausible actions might change those patterns.

It is timely to consider the next decade of air chemicals. The urgency of action to minimize the impacts of climate change and continued efforts to reduce air pollution in those communities most impacted means that there will be major changes to the emissions of chemicals into our atmosphere. The advent of new technologies for observing, displaying, sharing, predicting, interpreting, and communicating about air allows for the possibility of creatively reimagining how we develop and deploy new tools that comprise the ecosystem that allows us to have a shared understanding of the chemicals and particles in the air. It is our vision that these new tools will be used by air quality scientists, community groups, individuals, public health professionals, regulators, industry, and the many other stakeholders who need a common understanding of factors influencing the air.

The goals we lay out will be challenging, but that is no reason to set our sights low. Challenges include support for new kinds of measurements made by the people of California, and support for education about the availability and benefits of measurements from space-based platforms that are provided by NASA, ESA, and, in a recent development, satellite instruments launched by businesses and nonprofits (e.g., https://www.methanesat.org/). They include ensuring that all observations of air in California are shared on a common platform, accessible to experts and non-experts alike. Particularly difficult is providing context that allows for an understanding of changes over time up to the present day and setting expectations for the pace of changes over time in the future. Context is almost always a story-telling art and making it uniformly accessible is ambitious. Such context can be provided by comparison to nearby measurements or time series at the location of the measurement. Context can also be supplied through display of models that include an interpretive layer describing the factors that contribute to observed air quality and/or greenhouse gas (GHG) emissions, and indicate the situations where our understanding of those factors is excellent and situations where our understanding needs improvement. Beyond context, a new measurement ecosystem should support clarity in the assignment of responsibilities for poor air quality and contribute to assessment of whether decreases in air pollution and greenhouse gas emissions are proceeding at the pace necessary to achieve publicly stated goals of governments, candidates and businesses and community groups.

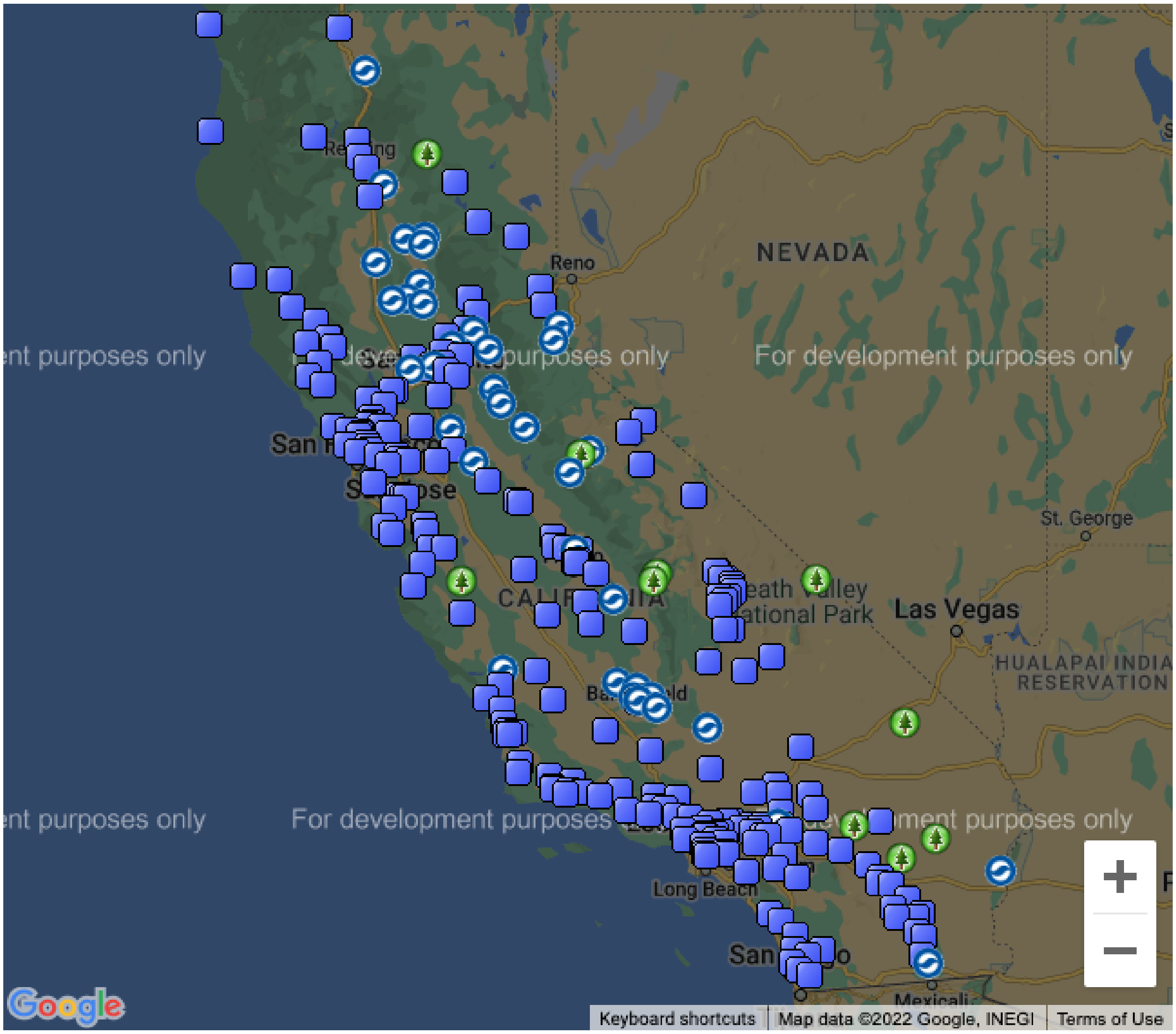
In the sections below, we propose a framework for approaching the evolution from the current air quality and greenhouse gas observing and reporting systems to one that will embody this vision of an air quality ecosystem. This framework describes new measurement opportunities, but places emphasis on parallel development of modeling and data science tools for the integration of models and observations and communication about the air. New measurements alone will be insufficient to achieve the goals we lay out. Open reporting of and creating meaning from the measurements that will be made is perhaps more challenging than making the measurements themselves. Accordingly, we recommend that as much, or more, attention and resources should be devoted to reporting and interpreting measurements as to new observations themselves. The synthesis of observations, model simulations, reporting, and increased accessibility that we describe are intended to support creative, thoughtful, and effective decision-making in the State of California and to ensure California remains the world's leader in cleaning our air, in reducing the effects of poor quality air on public health, and in reducing our impact on climate.

We begin with an overview of the existing air ecosystem and then turn to description of opportunities to reimagine the components and integration of the system.

The existing air ecosystem

The existing observing, modeling, and public communications systems used in California were, for the most part, designed decades ago and have been incrementally improved and integrated in a variety of ad hoc ways. Hundreds of locations with instruments for continuous, ground-based monitoring of ozone (O_3), $PM_{2.5}$, carbon monoxide (CO), NO, and NO_2 are supported by the state and local air districts. Some locations have measurements of a set of organic molecules, usually through collection and analysis of air in canisters every few days. Calibrated data from these locations is publicly available, but usually after a long wait for professional quality assurance and controls. Air quality observations are available from state websites (https://arb.ca.gov/aqmis2/aqdselect.php), at AirNow (https://www.airnow.gov/), and at other online locations. There is no one-stop shop for the full complement of observations.

A separate and more recently designed system exists for observing, tracking, modeling, and reporting absolute values and trends of GHG emissions. That system aims at statewide totals for CO_2, CH_4, and nitrous oxide (N_2O). It is largely set in rural locations and decoupled from the air quality observing system which is concentrated in cities. Figure 1 shows a map of the AQ and GHG monitoring sites supported by the California Air Resources Board (CARB) and local air districts.



This map was created using Google Maps API v3 by Eric Burton and Dustin Goto, Air Resources Board

Figure 1: Current AQ and GHG sites in CA, as reported on the ARb website: https://ww2.arb.ca.gov/applications/air-monitoring-sites-interactive-map.

Ancillary data such as local meteorology (https://www.arb.ca.gov/aqmis2/metselect.php) and characteristics of the on-road fleet of vehicles operating on the highways (https://pems.dot.ca.gov/) are also available, but through different systems. Other relevant data, such as fuel sales, permits for chemical use, and energy used for electricity and heating, are recorded and tabulated but not as easily accessed.

These ongoing measurement programs are frequently supplemented with short-term, ground- and aircraft-based measurements led by the research community. Those observations can provide much more detail than the standard observing systems, both in terms of chemical composition and spatial resolution.

Finally, over the past decade, a variety of novel measurement approaches have been pioneered, including those using new, lower cost or more portable sampling methods as well as those using much higher spatial resolution and more comprehensive measurements from satellites. Measurements from satellites (e.g., GOES, OMI, TROPOMI, OCO-2) are widely available and include measurements of aerosol, NO_x, CO_2, CH_4, and formaldehyde (CH_2O). The availability of lower cost measurement devices for $PM_{2.5}$ and gaseous criteria air pollutants has enabled a host of new observational approaches, although the data quality of these sensors are not as accurate and precise as regulatory- or research-grade instruments. These low-cost options include crowd-sourced sensor networks, of which the PurpleAir $PM_{2.5}$ network is especially notable for its high density of observation and public access to the observations, as well as the Berkeley Environmental Air-quality and CO_2 Network (BEACO_2N, http://beacon.berkeley.edu/) for its focus on urban CO_2 emissions (Apte et al., 2020; Mousavi & Wu, 2021; Caubel et al., 2019; Mailings et al., 2019). These new observational approaches also include community-led sensor deployments to understand local contrasts in air quality—many of which have been supported by California's AB617 Community Air Protection Program. Another notable innovation is the deployment of large-scale mobile air sensing using instrumented vehicles.

Successful air quality and GHG management requires precise and long-term measurements. The existing observing system was designed with these criteria in mind. The system relies on deployment of high-cost (both capital and labor), fixed-location monitors positioned to establish long-term trends of chemicals in regional/urban settings and to monitor impacts of high interest sources, such as vehicles, energy or chemical intensive industries, and fossil-fuel-based electricity generation. The network is designed so that we are able to trace the accuracy and precision of measurements over decades, allowing comparisons over space and time and providing the ability to measure small changes.

This observational network has supported crucial and important conclusions about air quality that form the basis for policy design and serve to evaluate the efficacy of policy. For some chemicals, observations dating back to the early 1960s are available. Since the 1960s, O_3, NO_x, some VOCs, CO, and $PM_{2.5}$ have all been dramatically reduced in California. With the introduction of modern catalytic converters, the last three to four decades have been marked by continued improvements in emission rates. For much of the last 50 years, emissions of NO_x and organic chemicals have decreased at rates of 7% per year (Winkler et al., 2018). This rate of decrease has held, even as the population of California and the number of miles driven per person per year have increased. As a result, every Californian is breathing cleaner air than was the case decades ago. In the most polluted locations, the air is cleaner and healthier than it was as recently as 10 years ago.

Nevertheless, some people are still breathing air that is cleaner than others. By some measures, the differential in exposure has not substantially narrowed, even as overall levels of O_3, aerosol, and other chemicals that contribute to poor health have decreased (Rosofsky et al., 2018). A new emphasis on thinking about disparities has brought attention to this fact, which local environmental justice advocacy groups have been working to bring attention to for decades. New approaches to documenting differences in air quality and GHG emissions focus on spatial scales of tens to hundreds of meters, distances that are small enough to allow recognition of near-road effects, pockets of industry, and neighborhood-scale differences in trucking activity. We return to these new observational tools below.

A second major foundational component of the air ecosystem is the collection of models used to collate our understanding of the factors that affect the chemicals in air. Modern computational models represent our understanding of how emissions and their sources, the shape of the earth's surface, forests and other natural environments, atmospheric transport, chemical transformation, and weather combine to affect the chemicals in air. Different types of models are used to describe these ideas. The most sophisticated models attempt to describe the concentration of chemicals as observed at specific points in space and time. These models combine separate components representing each of the aspects listed above (and others). For example, emission models are an important element of the air quality system. Some emission models are publicly available online either as direct data output or via a downloadable user interface, including mobile sources emission models like CARB's EMission FACtor (EMFAC) and the U.S. Environmental Protection Agency (EPA) MOtor Vehicle Emission Simulator (MOVES), the Hestia Project for quantifying CO_2 emissions, and the Anthropogenic Carbon Emissions System (ACES) for fossil fuel CO_2 emissions. These models attempt to describe the full detail of certain processes contributing to emissions into the air, and are then combined with models that describe chemical reactions and the mixing and transport of chemicals by wind (e.g., https://airquality.weather.gov/). Examples of these chemical weather models include WRF-CHEM, WRF-CMAQ, and GEOS-CHEM. Until recently, computing power limited the spatial dimensions of these models. They were digitized with pixels typically 12 km × 12 km or larger, preventing their application to some environmental justice questions. Case studies using models of this type have long been the basis for policy design, and have been used by the scientific research community to gain deeper insights into factors affecting the composition of air. However, models are much less accessible than observations. There is no regular posting of model calculations in a form where the public could compare them to observations. Moreover, even the most sophisticated users struggle to evaluate whether differences between analyses using models and observations can be attributed to choices made in the component models, to a poor representation of the weather, to the mismatch between measurements at a single point and the simulated concentrations in the larger area of a pixel in the model, or to something we just do not yet understand about the atmosphere.

Although it is less well recognized, the new emphasis on thinking about neighborhood-scale disparities in the composition of air has occurred simultaneously with increasing computing power that allows calculations that can assess differences within cities. It is now almost routine to perform chemical weather model calculations with 4 km × 4 km pixels, and it is straightforward to do calculations with 1 km resolution. Additionally, a number of other simpler models have been developed that rely less on first principles, but allow use of even finer resolution in the prediction, assessment, and interpretation of observations (Hamilton & Harley, 2021). The improved spatial resolution of models and that afforded by many distributed measurements allow us to document and explain similarities and differences in air quality and GHG emissions at the scales where people recognize differences. We return to these new modeling tools below.

Measurements and model calculations are the foundation of our understanding of the air ecosystem. We draw your attention to two other, less well defined but essential features: interpretation/synthesis and communication (Figure 2). Interpretation includes examining observational data and model output to describe air quality and GHG spatiotemporal trends, within the context of source and loss mechanisms, control technologies and regulations, and policy development. Interpretation is the collection of logic that allows a firm scientific basis for evaluation of the potential of policy to effect change, for an understanding of how a warming climate might affect the air, and for describing why the air is cleaner today than it was 20 years ago. Communication of observation and model data along with interpretation to all stakeholders is essential for creating a comprehensive and accessible air information system that can effectively guide future decision-making by individuals and organizations.

The future of observations and models in support of air quality management

Effectively managing air quality and greenhouse gases requires: (1) identification and quantification of primary emission sources; (2) regulatory and non-regulatory approaches to reduce identified source contributions; and (3) observations of chemicals in the air over long enough time periods to quantify emission trends, to attribute those trends to specific sources, and to evaluate those trends in comparison to publicly-stated targets. Typically, we are only able to measure the amount of chemicals or particles in the air and must use a model to link the observed concentration to emissions. The inaccessibility of models has resulted in a bias toward thinking about expanded measurements as a solution to democratizing air information. As we describe here, we imagine CARB's efforts over the next decade to include a renewed focus on ways in which models and observations go hand-in-hand.

Some might also add use of air observations and health data to provide quantitative guidance about health outcomes and risks of exposure to poor air quality. The latter includes the process for setting priorities about which aspects of the air to attempt to change. The air ecosystem we envision should support that priority setting, but we recognize it is a separate activity bringing individual and community values into contact with the scientific understanding we focus on in this whitepaper.

In this section, we describe the changing landscape of tools available. These tools form the basis for our recommendations in the following section, where we describe priorities for the evolution of current systems, including new sensors, satellite-based observations, and methods for multiscale integrated modeling that, in combination, would guide future thinking about management of air quality and GHGs. In our recommendations and evaluation of existing tools, we emphasize public access to observations, models and interpretative tools, and the opportunities for enhanced efficiencies in thinking about air quality and GHG management as a single system instead of parallel components.

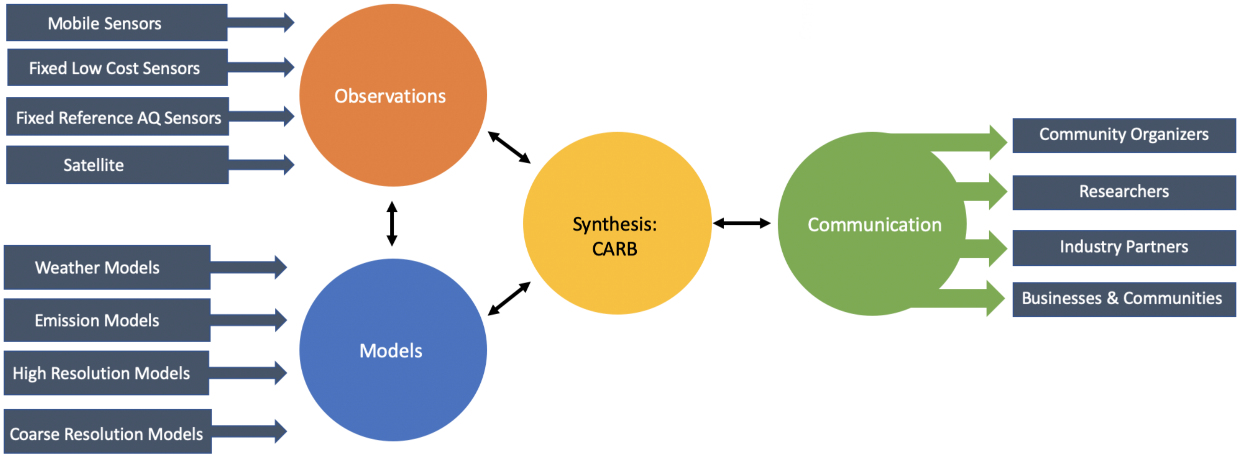


Figure 2: Schematic of the proposed air ecosystem

New observational tools

Observing the atmosphere with traceable precision and accuracy remains the province of high-cost equipment and specialized labor. New approaches allow for characterization of the air with unprecedented spatial resolution and with more complete spatial coverage than these existing approaches. These new observational approaches include low- and high-cost sensing methods. Some tools can monitor air pollutant concentrations continuously to track air quality trends over time and include an opportunity for citizen science, while others are satellite based or typically deployed in more technical, discrete campaigns that last a few weeks or months to better understand specific questions about air quality and climate science.

<u>Example #1: $PM_{2.5}$ sensing</u>

Some of these new tools are inexpensive, can be operated with negligible labor costs, and are already publicly accessible. For example, the PurpleAir sensor measures PM concentration, temperature, and relative humidity, and displays this data in real-time on a public website when the sensor is connected to the internet. One model includes an onboard data storage device that can be used to download data. The labor costs associated with this effort—fabrication of the devices, shipping them to users, developing and maintaining the web based interface, providing user support—are shared over many users' and provided by the initial buy-in rather than as an ongoing, subscription-based service. These sensors are distributed both indoors and outdoors, in some locations at densities of dozens per square mile. Research has shown that the manufacturing of the core sensor is so reproducible that improved understanding of the relationship between a single sensor's measurement of light scattering and its interpretation as $PM_{2.5}$ mass can be easily extended to all sensors that are in a similar environment (Alfano et al., 2020). These sensors presently cost ~$200–300 each and they are more densely distributed in wealthier communities (deSouza

& Kinney, 2021). However, the installed density in these wealthier communities is often in excess of what is needed to describe the spatial distribution of outdoor $PM_{2.5}$. Very modest investments from CARB to deploy these sensors in areas where they are lacking could result in transformative $PM_{2.5}$ measurements. The PurpleAir or similar sensors like the Dylos are also widely used in community monitoring, for example SJVAir (www.sjvair.com) in the San Joaquin Valley (SJV) and the IVAN (Identifying Violations Affecting Neighborhoods; ivanonline.org) reporting network in seven communities across the state.

Example #2: Low-cost, fixed-location chemical sensing

Most of the other low-capital-cost sensors for chemicals, including CO_2, O_3, NO_2, NO, CO, SO_2, and VOCs, are more difficult to use and interpret than the PurpleAir sensors. The generalizations regarding how to convert the voltage or current measured by one sensor are not easily applied to all sensors of that type. Thus, the labor of creating accurate measurements rapidly exceeds the instrumentation expense. With time, experience, creative instrument development, and new applications of artificial intelligence software, this is likely to change. These sensors are not as widely distributed as the PurpleAir sensors and the raw and processed data is not typically publicly accessible; the data that is available for these sensor systems is generally not aggregated on a common platform. Sensor performance has been explored (Baron & Saffell, 2017; Hossain et al., 2016; Wang et al., 2015; Shusterman et al., 2016; Kim et al., 2018). There are notable efforts by the South Coast Air Quality Management District (SCAQMD) and EPA to provide standardization of performance metrics (Jiao et al., 2016).

Use of these types of sensors in observing networks are proliferating. The low capital cost and AB617 have encouraged use of these types of sensors by the research community and have increased monitoring in communities that have been historically underserved and understudied. Examples of these dense sensor networks include BEACO2N (http://beacon.berkeley.edu), Clarity nodes (https://openmap.clarity.io/), the Real-time, Affordable, Multi-Pollutant (RAMP) sensor network (Zimmerman et al., 2019), and AB617-funded community projects like the Richmond Air Monitoring Network (RAMN; https://www.psehealthyenergy.org/our-work/programs/environmental-health/richmond/).

Example #3: Satellite remote sensing

At the other extreme are very high capital cost satellite remote sensing instruments. Instruments are typically paid for by NASA and ESA and the only costs (if any) to California are those associated with interpretation and communication. Measurements of NO_2 are the most widely used of these measurements in the air quality context (Streets et al., 2013; Martin 2008; Lange et al., 2022). There are also measurements of CO_2, O_3, CO, CH_2O, and $PM_{2.5}$. California is investing directly in a satellite to measure CH_4 as part of the program to manage GHGs in the state (https://ww2.arb.ca.gov/our-work/programs/california-satellite-partnership). Satellites are now providing, or will soon provide, hourly daytime measurements of NO_2, CH_2O, O_3, and $PM_{2.5}$ at ~1–3 km resolution (http://tempo.si.edu/; https://modis-land.gsfc.nasa.gov/MAIAC.html). CO_2, CO, and CH_4 measurements are also becoming available at high spatial resolution (e.g., https://www.jpl.nasa.gov/missions/orbiting-carbon-observatory-3-oco-3; http://www.tropomi.eu/). A major advantage of these instruments is that they are mapping instruments. Many of them provide early complete coverage of the entire planet making it simple to compare locations in cities to rural ones or to compare different neighborhoods in the same city.

As one example, exceptional progress has been made in satellite-retrieved aerosol optical depth (AOD), a quantity related to the amount of aerosol in a region. By incorporating new algorithms, the AOD retrieved from the MODIS (Moderate Resolution Imaging Spectroradiometer) instrument are now at much higher resolution than previously possible (1 km) (Lyapustin et al., 2018). Instruments on the GOES (Geostationary Operational Environmental Satellite) satellites and a new instrument MAIA (Multi-Angle Imager for Aerosols) also do or will soon contribute to aerosol information at comparable spatial resolution. A number of researchers have built simple relationships between these measurements and estimates of $PM_{2.5}$. (van Donkerlaar et al., 2006; Chudnovsky et al., 2014; Kloog et al., 2014).

The technological improvements in satellite imagery over the past decade increase the precision, scale, and accuracy of measurements and simulations based on satellite measurements. However the limitations of space-based imagery persist, in that it is often difficult to translate the quantity measured from space—typically measured as a column-integrated quantity representing the amount of material between the surface and the top of the atmosphere—into a surface-relevant quantity such as the contents of the air a person breathes. This is the point where integrating data across measurement systems becomes critical. Analyzing satellite data in conjunction with data from a hyperlocal sensor network over the same geographical area and time period would allow a calibration of sorts for these two datasets, which could then be used to extend the understanding of the relationship between ground-based and satellite observations to other cities where the only observations available are from satellites. At this point in time, there is a much higher proportion of cities with only satellite data than those that also have dense sensor network coverage.

Example #4: Driving and flying

Intermediate in cost between inexpensive networked instruments and satellite based instruments are methods for mapping air using instrumented mobile platforms, including aircraft and automobiles. Mobile monitoring with instrumented vehicles is becoming more common and delivering on-road maps of air chemicals and GHGs with ~50–100 m resolution (Apte et al., 2017; Hasenfratz et al., 2015; Sun et al., 2022). Aircraft are typically deployed in discrete campaigns with the aim of testing specific elements of our understanding of factors affecting chemistry of the air. Extensive ground-based experiments coordinated with aircraft during CALNEX (2010) and the RECAP (2021) field campaigns included extremely detailed observations of hundreds of chemicals in the air, allowing detailed assessment of the role of different types of activities and sources to regional O_3 and aerosol. Aircraft mapping has also been an important component of defining methane emissions (Karion et al., 2015; Sheng et al., 2018; Schwietzke et al., 2017).

Example #5: Multi-mode

Combining data and information from multiple sources to better understand air quality is an active area of research. A number of studies have, for example, combined data from low-cost sensor networks and regulatory monitors using Kriging and inverse distance weighting methods to improve estimates of ground-level spatial-temporal $PM_{2.5}$ concentrations and provide more detailed information about emission sources (1–3). Some statistical frameworks require supervision to generate high-quality results, indicating that more efficient strategies are needed. Further, quality control and data screening need to become more automated and systematic. Data from ground-level low-cost and regulatory-grade $PM_{2.5}$ sensors have been combined with satellite data. In one study during California wildfires (4), a network of low-cost sensors was used to develop statistical models to convert satellite-measured aerosol optical depth into $PM_{2.5}$ concentration with similar veracity to that obtained using regulatory-grade sensor data. Another study evaluated four statistical approaches to analyzing sensor data to inform future efforts to combine satellite and ground-level sensor data (5). Numerous studies have used mobile and low-cost sensor data to improve land-use regression model estimates of concentrations of a range of pollutants, including NO_2, NO_2, $PM_{2.5}$, and VOCs (6–11).

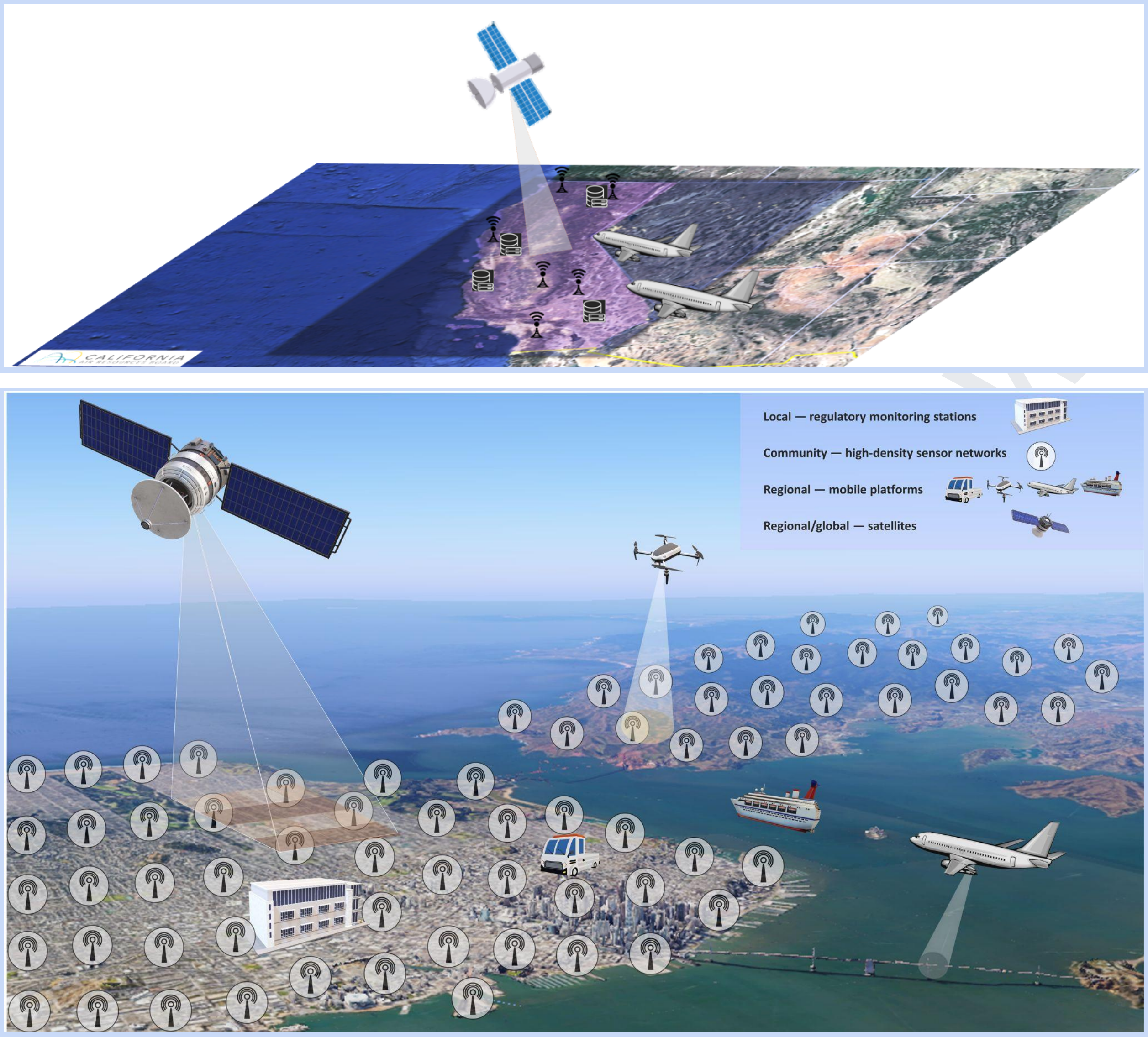


Figure 3: Schematic of combined observing system including satellites, aircraft, and low and high spatial density surface observations. Top Statewide view, bottom a zoom in to an urban center.

Figure 3 above provides a glimpse of the combination of new and old observing tools we have described. No one of these tools is adequate to meet the future needs of California. We require operation of many of them simultaneously to build the observing component of the air ecosystem of the future.

As an example of this type of tool, we suggest looking to recent papers that use response surface models fitted to the Community Multiscale Air Quality (CMAQ) model for inspiration. For example, Kelly et al. used a polynomial function in a response surface model (pf-RSM) fitted to CMAQ simulations over the eastern U.S. for January and July of 2016. The pf-RSM predictions were in good agreement with the out-of-sample CMAQ simulations (with some exceptions) and this work indicates promise for this methodology as a means of integrating measurements and building out tools for predictive modeling (Kelly et al., 2021). Similarly, Xing et al. apply statistical response surface methodology for a CMAQ analysis of ozone sensitivity studies, providing another methodological framework for integrating across multiple tools and datasets (Xing et al., 2011). As a final example, Wang et al. developed an NH_3

emission inventory for China in 2005 and applied the RSM technique to the CMAQ model, in order to successfully analyze the impacts of NH_3 emissions on fine particles over specified geographical and temporal boundaries. These data indicate that this type of integration is not only possible but can be used to successfully analyze emissions and make predictive recommendations based on the results (Wang et al., 2011).

New modeling tools

Not long ago, calculations using chemical weather models were only affordable at low spatial resolution like 25 km pixels or at higher resolution for short time periods like a few weeks. Additionally, defining the chemical concentrations at the boundaries of the model needed time-consuming consideration. Today, new tools allow high spatial resolution (~1 km pixels) and long time periods (years). Models of the whole Earth can be run at modest resolution (~25–50 km) and target areas can be embedded with high spatial resolution, obviating the need to spend special effort defining the boundary conditions at the edge of the region of interest (Giorgi, 2019).

Moreover, surface $PM_{2.5}$ concentrations are better simulated via enhanced representations of secondary organic aerosol and fine dust (Hammer et al., 2020). The development of a new, updated fire emissions inventory presents enhanced global coverage and higher resolution of biomass burning emissions (Wiedinmyer et al., 2011). Finally, considerable improvements to regional anthropogenic emission inventories of aerosols and aerosol precursors over the United States, China, and other areas in Asia produce enhanced time-varying information for recent years.

In addition to these new approaches using chemical weather models, other modeling tools are used that bring simpler concepts to the foreground. Models predicting air quality based on the underlying land use have been shown to be accurate in some contexts. Conceptual models that isolate key variables such as temperature, NO_2 concentration, and the number of trucks on the road have been shown to synthesize much of the history of poor air quality in the LA basin and SJV, and to offer predictions for how specific control measures might reduce the number of days with poor air quality (Pusede & COhen, 2012). Reduced-complexity models (RCMs) such as InMAP (An Intervention Model for Air Pollution), EASIUR (Estimating Air pollution Social Impact Using Regression), and AP2 (Air Pollution Emission Experiments and Policy) are yet another recent approach for modeling $PM_{2.5}$. These models provide a computationally simplified representation of mechanistic processes that lead from emissions to exposures, thereby permitting policy-oriented analyses of a broad range alternative mitigation strategies that are often not feasible with other full-scale models. Common applications for RCMs include assessments of solutions to environmental disparities and studies of air pollution and climate co-benefits (Tessum et al., 2021; Tessume et al., 2019).

In parallel with these advances, which have focused primarily on air quality and global atmospheric chemistry, a community of researchers has been pursuing high spatial resolution (~1 km) emission inventories for greenhouse gasses that offer complete coverage of the United States. Notable among these are the Hestia, Vulcan, and ACES inventories. Since urban emission inventories are generally not provided by states or the EPA, individual cities have developed their own protocols. Analyses show that when compared to a common method, these individual inventories vary widely; some are higher than common protocol while others are lower. Even when the two protocols are in close agreement about a total (e.g., Oakland), the division of emissions among sectors varies widely (Gurney et al., 2021).

New tools for interpretation and communication

Meaningful interpretation of observations and models requires accessible datasets across stakeholders. In particular, observational datasets must include contextual information of when, where, and how the observations were made. Such data can then be used as input for and validation of predictive models and to create visualizations that evaluate trends and policies, both of which are essential communication tools for an effective air quality management ecosystem.

Availability of observational and model data is one of the key hurdles for creating an integrated air information ecosystem. Many observations are being collected, some with state support, without commitment or facilities to provide a permanent accessible record. There are searchable and downloadable databases of regulatory data, including the EPA Air Quality System (AQS) and CARB’s Air Quality and Meteorological Information System (AQMIS), but these are not inclusive to all measurements of air quality made in the state. CARB will soon be launching AQView as an effort to centralize and display air quality data collected across the state, focusing on the community data collected as part of AB617 efforts. This AQView platform is a promising foundation for the framework we propose here. In addition to observational air quality and GHG data, an integrated air information system must also include key ancillary data that provides context for those observations, including parameters like temperature, rainfall, traffic counts, etc.

Visualizations of observations can include real-time maps of pollutant concentrations, a simple time series at a single location, comparisons between many locations at the same moment in time, and a movie of concentration time series at many locations (e.g., https://gml.noaa.gov/ccgg/trends/history.html). At times, only the observations are shown. Others apply smoothing between measurement points, which makes it easier to see patterns but can be misleading if the unobserved variation between observations can be large. Visualizations of models are not as widely available, but can include the same features for predicted values.

Recommendations for the evolution of the observing and modeling ecosystem

There is tremendous, understandable excitement around the availability and accessibility of new approaches to observing, describing, interpreting, and communicating about air quality and GHGs. Much of the excitement has centered on the ability of individuals or groups to choose where to observe.

We recommend CARB lead in the creation of a new vision. Our recommendation goes beyond the democratization of observations. CARB should lead in democratizing ***information and understanding*** about the chemicals in the air. This should be a joint effort of all of the communities interested in understanding the air.

CARB should also partner with health agencies to put the information in a form that can spur new epidemiological studies that take advantage of high spatial resolution of both new observations and models. These efforts should utilize the understanding we have in order to construct long time series that allow backwards extrapolation of that high spatial resolution data with confidence for long-term studies of the effects of air pollution exposure. An associated initiative should focus on creating tools that allow individuals to create assessments of their own personal health risk.

We recognize that the State has limited resources and that any strategy employed will involve making trade-offs between desirable features of an evolving air information system. We also recognize that many of these recommendations may be outside the scope of CARB's current technological and resource capacity. Even so, these recommendations are a target that we should strive to attain, and CARB must lead the way in devoting more research and development to reach those goals. The following list of recommendations is in order of priority.

Recommendation #1: Radically increase transparency and accessibility of observational and model data

A. Open access to raw and calibrated observations for air quality and GHG observations should be a minimum standard for any measurements supported by the state. A common platform that allows anyone receiving state funding to share their observations and have them displayed and accessible to the public should be developed. This is an urgent need and CARB should ensure that a beta version is available by the end of 2023, if not sooner. Design of the platform should emphasize ease of use. Dedicated staff support to help ensure that measurements with state funding are all uploaded promptly and with adequate metadata to appear properly in the shared database will be necessary. The ease with which a user contributes sensor data and then views their own and other data on the public PurpleAir website should be the standard for accessibility the platform aspires to meet or exceed.

B. This platform should also incorporate observations of California's air that the state is not directly funding, such as satellite observations from NOAA, NASA, or ESA, and networks of publicly available measurements such as PurpleAir and BEACO_2N. CARB should use its influence to encourage others who are not currently making their data public to share their data in this same common platform. CARB should promulgate modern data standards that make it easy to integrate observations by others. The labor costs for sharing must be low enough that users who are not funded by the state do not make their decision to share based on that cost.

C. Model inputs and outputs for air in the state and the tools used to create them, including models of emissions, should be as easily accessible as observational data. This could occur by use of the state's resources to create an air quality analysis database that is archived and accessible, and/or by creating a California portal to the NOAA national air quality forecast and analysis system. The user should be able to view observations and model inputs/output at the same locations with ease.

D. In the same platform that archives observations, standard visualization tools for showing concentration changes over time at any location in the state should be available. The standard visualizations should be responsive to priorities set by a variety of constituencies and clearly illustrate differences within and across neighborhoods. They should include the ability to look at trends overy many years. They should, for example, allow comparison of the most recent 7 days to the same 7 days last year and/or the average week at this time of year. There should also be a tool to develop and upload user-supplied analyses. The most popular ones should find their way to the top of the menu.

E. Finally, the user should be able to examine the effects of policy options on the variables they care about. For example, how do concentrations and exposure change if emissions from an industrial facility or from trucking are reduced, or if zoning is changed so that no one lives within 250 m of a highway? We note that parametric displays of models run under multiple emission scenarios have been created for this purpose.

Recommendation #2: Integrate the tools for building and assessing air chemicals and GHG emissions

A. Inventories of emissions used by the state for air quality and GHG emissions should be embedded in the same framework. Analysis of observations and models that leads to new insights about CO_2 emissions should immediately benefit our understanding of air quality and vice versa.

B. Traffic observations by publicly funded institutions such as Caltrans are common but difficult to access. Caltrans and CARB should collaborate to make this data more accessible and usable for the general public. These data should be directly coupled to emission inventories so that estimates of emissions in the past are tied more closely to hourly activity.

C. Ensure that CO_2 inventories meet the needs of registries and city planners. California is leading the nation in development of strategies for reducing CO_2 emissions. In contrast, our ability to describe CO_2 and CH_4 emissions in our cities is lagging. CARB should commit to developing a statewide inventory with 1 km or better spatial resolution and hourly time resolution (or collaborating nationally on such an inventory) and to the observations and analyses that would either confirm that commitments to reduce CO_2 and CH_4 emissions are occurring as planned or provide rapid guidance for changes in strategy that would meet the state's targets.

Recommendation #3: Increase the number and accessibility of observations and models in high-population cities across the state.

A. Ensure every city with a population over 100,000 people has observations and modeling that eventually lead to 1 km scale (or better) maps of criteria air pollutants and GHGs. To the extent that is a challenge for CARB to resource. CARB should partner with the academic community especially in areas of machine learning and AI to bring new efficiencies to modeling efforts.

B. Map other important chemicals in all communities with above average health risks.

C. Aim to minimize within-city disparities in data availability and quality, such that adequately resolved information is available regardless of community income, racial/ethnic composition, CalEnviroScreen score, etc.

D. As an example of this type of tool, we recommend that CARB look to observational systems such as Purple Air, BEACO2N, and similar projects that provide high-spatial-resolution measurements of air pollutants and GHG emissions via large numbers of sensors placed in close proximity to each other across high population areas. Expanding such networks provide block-by-block air quality information at high temporal resolution that is shared with the general public, allowing the monitoring system to serve a broad audience of constituents, including community organizations, academics, politicians, and individuals, simultaneously and effectively.

Recommendation #4: Provide incentives and support for neighborhood scale air quality and GHG management

A. Report model and satellite assessments of neighborhood-scale air quality in advance of new studies. Provide support to teams funded by AB617 so that all involved have a common baseline of understanding based on model and satellite data describing what we already know about the air in the region and have a strategy for translating new observations into improved models. This will more efficiently and effectively enable an improved understanding of that neighborhood's air quality, and help to translate what is learned to other neighborhoods in the state with similar/ common features.

B. Encourage continued development and evaluation of low-cost sensing methods and sensors.

C. Explicitly recognize the synergy between AQ and GHG management at neighborhood scales and prioritize support for observing programs that leverage that synergy.

Recommendation #5: Report progress toward goals using understandable and scalable frameworks

A. The ozone hole communication (https://earthobservatory.nasa.gov/world-of-change/Ozone) showing annual variation and long term improvements is a model for communication about atmospheric composition change. Develop and test analogous communication for surface O_3 and $PM_{2.5}$ air quality at regional, city, and neighborhood scales.

B. The transition to a low carbon future will touch the lives of Californians in many ways. Develop reporting for CO_2 and CH_4 emissions that allows people to see how progress is being made toward achieving climate goals. Assess and report on any negative consequences on air quality associated with the transition.

Recommendation #6: Add CO_2 monitors to the state's existing regulatory monitoring network

A. The addition of CO_2 measurements would allow estimation and tracking over time of integrated fuel-based pollutant emission indices that would help in verifying emission inventories.

Recommendation #7: Encourage usage, analysis, synthesis, and intercomparison of the full range of new observational datasets. Develop mechanisms to incentivize the regular analysis and interconnection of multiple distinct data streams generated by the observation system.

A. Develop an organizational data use plan that identifies and supports key user constituencies within and outside of CARB for data generated by this new observation system.

B. Major CARB reports on air quality trends should as a best practice always include intercomparison of evidence from multiple data sources, including conventional measurements, dense in-situ observations, satellite data, and models, with an eye towards highlighting areas of divergence and concordance between insights from distinct data streams.

We recognize that the recommendations in this report require substantial effort and resources. Therefore, in Figure 4 below, we lay out a recommended timeline for implementation that prioritizes our recommendations based on their potential impact, as well as their logical sequence. We recommend that implementation of these recommendations be completed by the end of 2030.

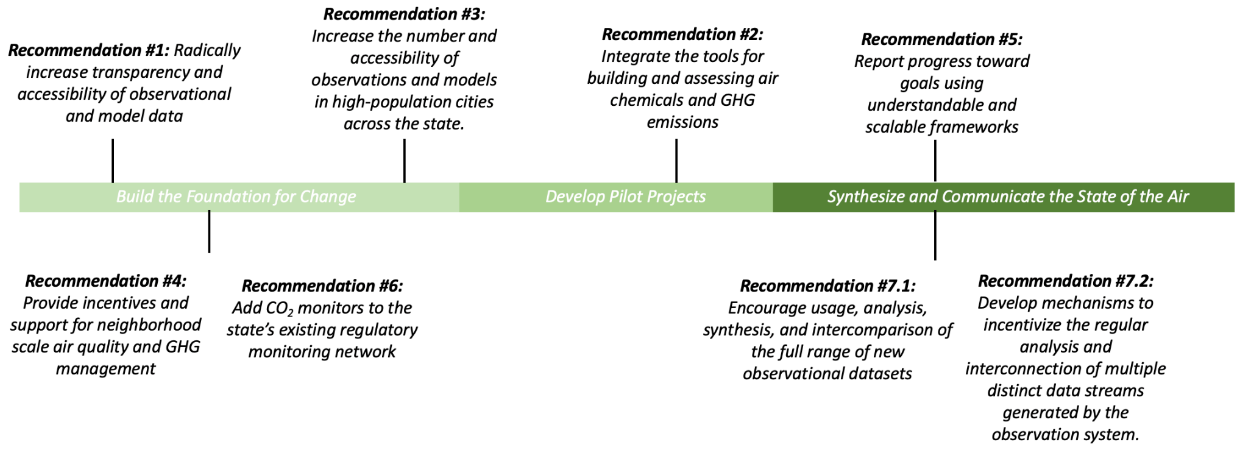


Figure 4: sequential view of this report's recommendations.

Summary and metrics for success

In this white paper, we describe priorities for CARB investments in the air quality ecosystem over the next decade. These priorities emphasize democratizing information about the air from sources including sensors installed by individuals and groups in their location of interest, the existing air observing networks supported by the state and local agencies, and satellite-based measurements. Concurrently, models that provide context at the space and time scales of interest for individuals, communities, and other stakeholders must be made available. That way, observations do not sit in a vacuum, but can build on the wealth of knowledge about the air embodied in chemical weather and other models. Finally, we emphasize investments in interpretation and communication. Models for interpreting and communicating a synthesis of observations and models that could be a guide for this effort include NASA's ozone hole resources, NOAA's CO_2 resources, and others. It is essential that communication not be an afterthought but a well-funded, ongoing investment.

Metrics for success of this effort should include:

1) Demonstration that an increasing fraction of all air observations in the state are shared on a common platform along with model output that aids in interpretation.
2) Evaluation of the ease of use of that common platform. The results of evaluation should confirm a commitment to continuous improvement in the user interface. Users should be able to easily review FAQs about the air as applied to their location of interest. New questions posed by users should be openly cataloged and curated so they can be promoted to FAQs if they are of wide interest.

A common, science-based understanding of emissions and air concentrations remains at the heart of our dialog about appropriate policy and individual action aimed at reducing GHGs and improving air quality. We hope that this white paper spurs creative thinking in support of this goal and we thank CARB for the opportunity to share our thoughts.

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