NOAA SCIENCE ADVISORY BOARD REPORT ON AIR QUALITY IN A CHANGING CLIMATE: NOAA'S ROLE

PRESENTED TO THE NOAA SCIENCE ADVISORY BOARD

BY THE SAB CLIMATE WORKING GROUP

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Climate Working Group Report

In support of the NOAA Science Advisory Board

Air Quality in a Changing Climate: NOAA's Role

White paper on enhancing the role of the National Oceanic and Atmospheric Administration in observing, understanding, and predicting the impacts and interactions of air quality with the Earth's changing climate through improved earth system prediction.

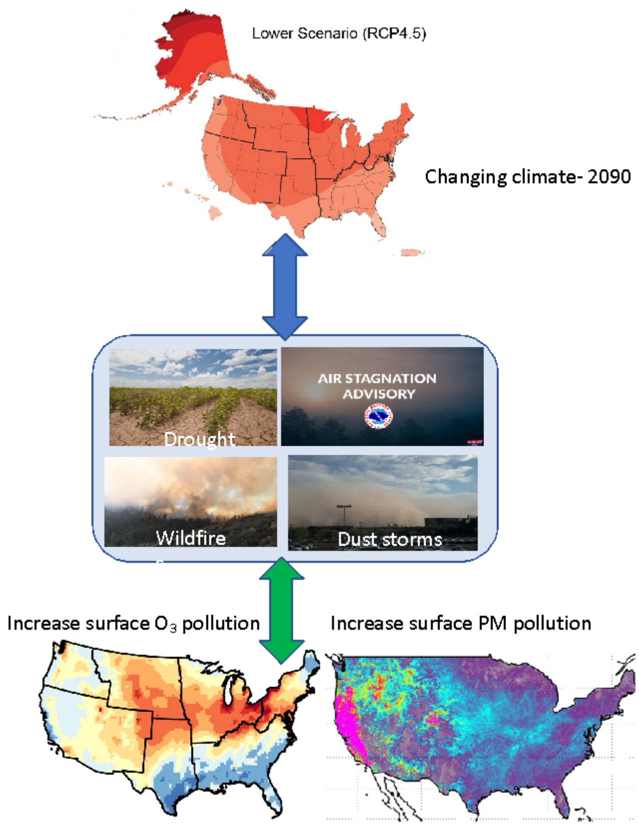

Figure 1: A schematic illustration showing the impact of climate change on air quality and of air quality on climate change. The figure shows the connection between climate change projection at the top of the figure, the impacts in the middle, and increased ozone pollution and PM changes. The PM and ozone changes are only illustrative and not specific calculations for a given scenario. (Illustrations from taken from the Climate Assessment (2018) and David and Ravishankara (personal communication).

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The imperative

NOAA has long been a national and international leader in research on the Earth's climate and its changes. It has also been a leader in earth system prediction, which is part of its mandate. NOAA has also been active in air quality research, observation, modeling, and predictions. The Oceanic and Atmospheric Research Office (OAR), National Weather Service (NWS), and National Environmental Satellite, Data, and Information Services (NESDIS) significantly contribute to air quality research. The NOAA Climate Program Office (CPO) now serves as a focal point for these activities. Air quality work is less heralded than climate, but it is still integral to climate and weather changes and their societal impacts. It falls squarely under NOAA's stated goal of: "**To understand and predict changes in climate, weather, the ocean, and coasts.**" Especially, air quality comes under NOAA's desire to meet the goal of **"...***the application of this understanding to such issues as the causes and* ***consequences*** *of climate change, ...the ability to model and predict the future states of these systems*." (https://www.noaa.gov/our-mission-and-vision) Air quality degradation is one of the major consequences of climate change and is often called the "climate penalty." Therefore, including air quality prediction in NOAA's earth system modeling prediction is an essential goal.

Air quality is primarily a human health issue, with other impacts such as visibility, ecosystem health, agricultural yields, and the well-being of wild and domestic animals. Even though air quality regulation is the bailiwick of the US EPA, science-based agencies such as NOAA have been enabling (through research) safer air for the country's citizens and, indeed, the world. Air quality degradation has been identified as a critical contributor to disease and death. Many studies suggest that marginalized and poorer communities have worse air quality, suggesting environmental justice is closely tied to any adverse impacts of climate change on air quality.

Climate change is one of the current existential issues facing the world and the country. Climate change is felt through its many impacts, such as changes in extreme weather, drought, sea level, etc. Climate change is also felt through changes in air quality. Further, most air pollutants are climate-forcing agents, especially short-lived climate forcers. The climate-forcing agents and air quality often have the same sources, e.g., fossil fuel combustion.

NOAA's goal is to predict the future of our planet through earth system predictions. Such predictions include predicting events that impact people, ecosystems, and infrastructure. Air quality directly affects people and is also one of the critical pathways through which climate change is felt. Therefore, air quality falls under the portfolio of earth system predictions

Climate and air quality are closely coupled and expressed as: (1) How does the changing climate alter air quality? (2) How do actions taken to improve air quality influence climate change, and how do actions taken to mitigate climate change alter air quality? and (3) How do actions to adapt to climate change affect air quality? As extreme climate events, such as heatwaves, drought, and resultant fire weather, become increasingly frequent and intense in a warming world, their impacts on air quality, public health, and the U.S. economy become increasingly impactful, geographically far-reaching, and costly. Therefore, NOAA must examine its portfolio on how air quality will change in a changing climate. Such an examination should address the challenges of monitoring, understanding, and predicting air quality in a rapidly changing climate. This document focuses on the research carried out in-house at NOAA and those funded by NOAA on air quality, related aerosol emissions, and connections to the Earth's climate. The main focus here is on the impact of climate variations and changes on the air quality of the United States and its territories, with some discussion and recommendations related to aerosol processes.

The changes are predicted and projected across various spatial and temporal scales, including the sub-seasonal to seasonal, interannual, decadal, and century timescales. The major climate-change influencers of air quality include: (a) stagnation periods and heat waves; (b) wildland fires (including influence by drought, precipitation, and fuel load changes), and their effects on air quality (we will not address the changes in land management or atmospheric CO_2 due to wildfires, even though these are important research topics); (c) inter-continental transport and its changes that will inevitably influence air quality across the United States and its territories; (d) desertification of terrestrial biosphere and agricultural dust and (e) urban-rural interactions and interfaces. These impacts are highly interconnected. Other changes, such as increases in pollen from the terrestrial biosphere may also be important. The science needs emerging from these impacts are described in the Appendix. NOAA is positioned to observe and predict these impacts as a part of their Earth System Prediction implementation in high-resolution coupled chemistry-climate-modeling. Indeed, coping with air quality in the future with a changed climate could be viewed as a climate adaptation strategy.

***NOAA has a significant opportunity to champion, lead, and coordinate amongst federal agencies the research needed to enable the Nation to effectively cope with and predict air quality in the changing climate through its mandate for earth system prediction*.**

Key Factors and Considerations

NOAA's research is necessarily determined by its mandates and goals. Therefore, we considered the following questions regarding current directions in developing our recommendations.

- How does air quality in a changing climate relate to current NOAA mandates and existing (and expected) capabilities?
- What are NOAA's capabilities that directly help address air quality issues now and in the future (i.e., in a changed climate)?
- What new technologies and modeling capabilities are necessary to enhance NOAA's air quality monitoring and prediction to meet mandates in a changing climate?
- Are new NOAA programs or add-ons to current programs needed?
- What aspects of NOAA's research are sufficiently ready to implement products?
- Where might there be significant overlaps with other federal and state programs such that NOAA may defer to other agencies or work jointly with them?

Even though these considerations are not discussed explicitly in the text below, they were central to the deliberations and recommendations.

▪ Current State of NOAA Science that Bears on the Research of Air Quality Now and the Future Changing Climate.

NOAA, through its OAR laboratories and cooperative institutes, has significant capabilities in air quality research. This includes observational capabilities, process understanding, modeling, and interpretations. Observational capabilities extend from developing instrumentation, in-situ sampling of chemicals, and measurements of meteorological variables. These are accomplished primarily through aircraft and shipboard campaigns, well-equipped ground stations (some of which monitor essential climate variables), and laboratory facilities. NOAA's NESDIS has many satellites that bring to bear on air quality research and observations. These observations are coupled with their modeling and analysis efforts. The National Weather Service has developed capabilities for predictions central to air quality. These in-house capabilities are closely connected with NOAA's research support through extramural funding. Despite not being heralded explicitly, NOAA has a wide-ranging air quality research effort. NOAA has also partnered successfully with other federal and state agencies and should continue such collaborations.

From an earth system prediction perspective, many components are inadequate for future air quality predictions and projections, as shown in Figure 2. The current linkages are gray arrows, and red arrows indicate what is needed. Many of these arrows fall within the purview of NOAA and its earth system prediction mandate. The future air quality prediction must address the noted linkages (red arrows).

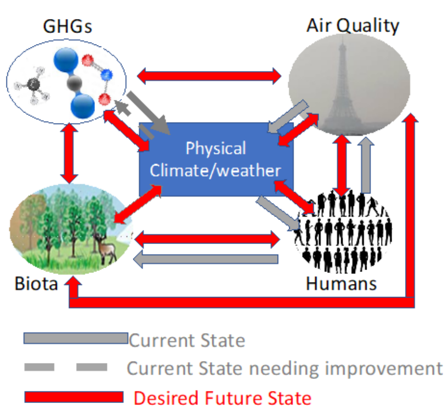

Figure 2: A schematic of the linkages between the various components that influence air quality and need to be included in NOAA's earth system prediction portfolio. The gray and red arrows show the current and desired future states. The dashed gray arrows indicate the coupling is included now but requires improvements. (Adapted from Natalie Mahowald.)

▪ Gaps in NOAA's Portfolio

As noted above, air quality research is within the portfolios of various federal (and indeed some state) agencies. These organically grown capabilities rely on (and often augment) other goals of many federal agencies such as USDA (Forest Service), NASA, EPA, DoE, and NIST. The CWG considers this shared research effort to be a healthy approach. We expect many gaps noted below to be partially met by such agencies. Yet, we believe that the gaps below hamper NOAA from meeting its goals and those of the nation.

- NOAA can be essential in researching the composition of air pollution (as a function of time and space) and their transport. Increasing such activities would provide critical information for science and policy. It would also enhance NOAA's role in informing policies to mitigate air quality degradation and adapting to the inevitable changes due to climate change.
- NOAA already plays a crucial role in drought research and predictions. Yet, it does not appear that the drought work is currently connected to the air quality predictions. The interactions between air quality and droughts, extreme precipitation, and humidity changes are essential.
- Other influences on air quality include heatwaves, desert and agricultural dust, allergenic pollen, wildfires, and their compounding effects. These factors, especially wildfires, are closely connected to drought and heat waves. On the flip side, extreme precipitation/high humidity has caused major pollen events and overloaded hospitals with people with respiratory problems. These additional influences must be considered to improve understanding, modeling, and predicting/projecting air quality impacts in a changing climate. This area is poorly understood, partly because there have been too few observed examples to identify their shared origins and model their co-occurrences with robust statistics.
- There is a lack of integrated studies on how physical and biological climate-related processes affect air pollution. In addition, many processes underpinning the impact of extreme climate events on air pollution are also not represented well in the most current climate and air quality models; often, they are not included at all. Numerous barriers exist among disciplines and between researchers and decision-makers in the study and risk management of the interconnected climate extremes and air quality.
- Air quality is essentially a boundary layer issue (emissions mostly occur in this region, people live there, and other impacts such as visibility are important for this region). Therefore, enhancements in boundary layer science, modeling, observations, and processes are needed to understand better and improve forecasts/predictions. The 2017-2027 National Academies of Science Engineering and Medicine (NASEM) decadal survey for Earth Science and Applications from Space (ESAS 2017) identified the development of better observations of PBL thermodynamic properties as one of the main priorities. ESAS 2017 called out for observation of temperature and water vapor profiles in the PBL and PBL height.
- It is imperative to consider what happens outside the territorial boundaries because they influence, or can influence, air quality within the United States. Further, it is crucial to know how U.S. emissions impact our "neighbors." Such interactions occur relative to close "neighbors" such as Canada and Mexico and from faraway places such as Asia and Europe. Efforts to understand these contributions are currently inadequate.
- The current air quality forecasts extend to about two days (48 to 72 hours). However, more extended forecasts (like weather and climate predictions from two weeks to one or two seasons in advance) have significant societal benefits. Further research is needed to determine if there is predictability beyond the 2-day time scale for many air pollutants. We may have sufficient skills at predicting inversions or warmer than usual days and hence some bad air quality days. Even though NOAA plans on such

longer-range forecasts, research in this direction appears insufficient. This is a gap not only for NOAA but other agencies.

- NOAA is at the threshold for exploiting new satellite data (e.g., GEO-XO). The groundwork needed to fully utilize such data ahead of their availability is essential. Efforts are required to fill the gap of roughly a decade between now and the availability of the highly spatially and temporally resolved satellite data.
- Many bad air quality events are associated with stagnant conditions. Our ability to forecast stagnation conditions, another weather extreme, needs improvement.
- Many anthropogenic, dust, and wildfire air quality events preferentially impact marginalized or poorer communities where observations are often sparse. Thus efforts to improve air quality observations and prediction for these rural and urban communities may contribute to reducing environmental injustice.
- Researching and quantifying ozone and PM formation during winter and understanding the sensitive urban-rural interface are essential for dealing with winter-time air quality degradations, a newly observed phenomenon. Attention must be paid to the ever-expanding urban-rural interface to decipher how air quality will be altered in the future climate.

Recommendations

A Call to Action

The committee lists various actions, at different levels of granularity, to enable better air quality information in a changing climate for policy, management, and adaptation. We recommend that NOAA convene a workshop to take stock of its air quality related activities, prioritize, and work out ways to advance the research and products to enable the US to cope with the air quality in a changing climate. We also recommend that such a workshop should have NOAA researchers and managers, and representatives of other Federal and State agencies, academia, and NGOs working in this area.

Overarching issues

Even though NOAA has a significant portfolio of research efforts and some products, there appears to be no central coordination effort in air quality research. In addition, funding for much of the air quality research effort seems to be ad-hoc or based on supplemental funding. These two factors have greatly limited NOAA's reach in air quality research and product development.

Therefore, we recommend that:

1. *NOAA would be benefited from a coordination office to utilize its research and product portfolios fully*. NOAA can first fully assess all the air quality related activities within NOAA, estimate the resources needed to meet NOAA's imperatives, and plan for future research.

2. *NOAA should provide sustained funding for research on air quality in a changing climate.* Such a provision can significantly advance its air quality mission and products.
   The above two overarching changes will enable NOAA to bring its scientific expertise to the table with the other agencies involved in this critical national issue.
3. *NOAA could support targeted early-career researchers working to increase the understanding of these relationships, especially relative to drought, heat, and wildfire*. Such support will help overcome current shortages in expertise in air quality-climate interactions. NOAA could also develop vital long-term collaborations with drought and wildfire managers to sustain research programs that effectively address these societally impactful problems. We note that a similar program for climate research is very successful.
4. *NOAA should enhance coordination with various state air quality agencies, understanding their needs, using them as stakeholders, and leveraging state and private sector resources*. NOAA has extensive experience coordinating weather, fisheries, and ocean services with stakeholders. Necessarily, this effort has to include other federal agencies. *We recommend that NOAA take up the mantle of predicting air quality in a changing climate and champion such research across other federal agencies.*
5. *NOAA should develop a close working relationship with the epidemiology community working on the air quality's impact on humans, such as NIH, CDC, and EPA*. This is because air quality is primarily a health-impact issue. The knowledge of what is needed for assessing the impacts of air pollution and its mitigation is central to prioritizing research and usable products. Including the concerns of traditionally marginalized communities in formulating the plans and communicating public health efforts are vital to enhancing environmental justice.
6. *NOAA should establish a dedicated Societal Benefits Office to facilitate transitioning air quality research to applications and engage practitioners such as air quality managers, disaster response teams, and health professionals in (d) and (e) above*. It could also incorporate this effort within an expanded initiative within CPO's current Climate and Society Interaction (CSI) program. It should also leverage and coordinate with other programs in Federal Agencies, such as the NASA Applied Sciences in Health and Air Quality (https://appliedsciences.nasa.gov/what-we-do/health-air-quality), to save time and resources.

Below are some specific recommendations for enhancing air quality research and products in the near future.

Climate extremes and air quality

1. *NOAA should leverage current knowledge and prediction capabilities in air quality and climate and its change to identify low-hanging fruit to make tangible progress in addressing the impacts of climate extremes (e.g., heat waves and droughts) on air quality*. (Note that these extremes also lead to events such as wildfires.) For example, the NIDIS and NOAA drought task force could take on evaluating drought's impact on wildfires and air quality as a priority. (The current funding does not appear to include this critical connection.) More air quality-relevant

information on drought, extreme precipitation/humidity, heatwaves, and air stagnation (which we classify here as an extreme weather event) can be provided by collaborative research co-sponsored by NOAA climate and air quality programs. Establishing interdisciplinary observational capabilities, especially leveraged by existing observational networks and through new interdisciplinary field campaigns, is central for enabling process studies and supporting model development related to climate-wildfire-air quality coupling, especially through an earth system approach.

Wildfire, dust, and pollen

2. *NOAA should enhance collaboration between the air quality, heatwave, and drought research communities through, e.g., joint calls for cross-disciplinary research or a task force consisting of air quality, heatwave, and drought researchers*. Dust and wildfire emissions have been recently shown to drive many bad air quality events in the US. Dust and wildfire emissions depend on meteorology and thus could be amenable to better predictions. However, it is unclear if the existing emission models for either wildfires or dust are sufficiently accurate to improve the air quality forecast. Therefore, hindcasts could be used to examine the abilities of existing models. The predictability of wildfire and dust emission events is unclear beyond the 1 to 2 day time scales. Examination of the event predictability is necessary. Such work should be done in collaboration with other agencies and researchers outside NOAA. The use of a test-bed concept may be worthwhile.
3. *NOAA should develop ways to provide information on the connections between drought (and its predictions), weather patterns, desert and agricultural dust and wildfires, and degradation in air quality to enable air quality projections over multi-year time scales*.
4. *NOAA should examine dust generation by human activities in sensitive areas.* Dust from agricultural sources, likely important in some regions of the country, is poorly understood and understudied. This work could be carried out in collaboration with non-NOAA researchers (e.g., USGS or universities).
5. *NOAA could contribute to the information on precipitation and pollen transport*. Pollen exposure sends many people to hospitals and is a significant health issue for people sensitive to pollen. Changes in pollen in a changing climate are likely to be an issue of concern with precipitation changes in the future. Additional factor includes the replantation of trees, especially those producing pollen. However, other agencies should likely take the lead with NOAA's partnership.

Boundary layer processes

6. *NOAA should enhance work on atmospheric boundary layer (ABL) dynamics to include better the processes in quantifying emissions (which mainly occur in the ABL.), mixing between the ABL with the free troposphere (both at night and during daytime), and inclusion of these processes in the models*.
7. *NOAA should aim towards sub-seasonal to seasonal forecasting of the ABL height*. This goal can be achieved with a moderately long (decadal) measurement record. The height of the ABL and the corresponding ventilation coefficients in models

play vital roles in the skill of air quality models. Recommendations to develop an observing system that improves the estimates of ABL globally and over challenging conditions, including (i) unstable, non-homogenous, and non-stationary ABL (ii) ABL under cloud cover; (iii) ABL over complex terrain, will have significant benefits for air quality modeling and forecasting.

8. *NOAA should lead an effort (involving other countries and modeling agencies) to craft a strategy involving a constellation of geostationary satellites, multiple low-cost cube- and small-satellites, airborne campaigns, and ground stations to fill many gaps in these observations*.

9. *NOAA should aim to utilize its vast expertise in in-situ and remote measurements of chemicals (with varying lifetimes) and aerosols to utilize chemical detection to characterize ABL dynamics*. Further, such measurements can be used to characterize emissions of chemicals better.

We note that the ABL research will help not only better air quality predictions but also a vast array of products that use climate and earth system models.

Observations and analysis

10. *NOAA is encouraged to support domestic and international teams focused on synthesizing observations and global models examining air quality and understanding intercontinental and interhemispheric pollution transport*. Currently planned geosynchronous satellites making measurements of air quality parameters over North America (TEMPO, GEO-XO), Europe (SENTINEL IV), and ASIA (GEMS) at high temporal resolution will significantly advance our understanding of air quality over most of the planet. NOAA should take a leading role in synthesizing and utilizing this data for air quality related research.

11. *NOAA should continue to develop and improve instrumentation that defines the gold standard of atmospheric gas and particle sampling to stay at the forefront of the field*. We recommend that NOAA design the next generation of sensors with the spatial and temporal resolution required to address the needs noted in the Appendix.

12. *NOAA, in coordination with other agencies, should evaluate the U.S. needs for sustained, long-term measurements to monitor tropospheric and near-surface ozone*. Enhanced ozone and water vapor sampling through the troposphere and stratosphere would contribute to developing air-quality forecasting capabilities. Enhanced studies on the impacts of stratosphere/troposphere exchange, biomass burning, and long-range transport on tropospheric ozone are also needed.

13. *NOAA should lead field campaigns using airborne, ground-based, and ship-borne platforms to measure the size distribution, composition, and optical properties of atmospheric aerosols to better understand sources, atmospheric processing, and impacts on radiation*. (This work could focus on the role of dust aerosol as ice-nucleating particles, the time-dependent radiative properties of biomass-burning aerosol, and the sources and climatic relevance of newly formed particles. Such research will also enable satellite and model validation, including air quality and cloud modeling. Importantly, it will also inform the assessment of the Earth's

radiation budget and hypothetical strategies for and detection of climate intervention.)

Model development and evaluation

14. *NOAA should continue to evaluate its operational weather and air-quality models and expand on this work to evaluate atmospheric composition in research, operational, and regulatory models against various observations (e.g., from the surface, aircraft, and satellite instruments) with a common framework.*
15. *NOAA should, in coordination with other federal agencies, aim to enhance modeling capabilities for multiple days to months to forecast air quality*. As a part of this effort, an improved understanding of emissions and fluxes at high spatial resolution is needed. In addition, increased effort is required in chemical mechanism model development, working toward an operational and regulatory model that incorporates the latest science and accurate representation of multiphase chemistry. For example, efforts are needed to improve analysis and forecasts of wildfire smoke and emissions and impacts on air quality.
16. *NOAA should increase capabilities in larger-scale weather and climate models to enhance the treatment of aerosols' physical and chemical interactions in the atmosphere, including fine-scale physical and chemical processes such as aerosol-cloud interactions*.

Air quality forecasts

17. *NOAA should test the ability of air quality models to simulate events in a hindcasting mode to evaluate forecast capabilities*. Forecasting air quality at longer than two-day time scales could provide substantial benefits. We may already have good skill at identifying events such as inversions or anomalously warm days sufficiently well that bad air quality days from anthropogenic pollution could be predicted.
18. *NOAA should explore the feasibility of a seasonal air quality outlook relative to extreme events to harness research interests in science questions central to improving predictability and model capabilities and applying the latest air quality science to address urgent societal needs*.
19. *NOAA is encouraged to develop a framework for air quality outlooks out to ~6 months, taking advantage of the predictability of ENSO, MJO, droughts, etc., and their relationship with air quality (including atmospheric stability, soil moisture, wildfires, and ozone)*. The advancing prediction has been effective by cultivating intercomparisons among research and nascent operational efforts (such as the origins of the NMME and the Sea Ice Outlook). Support research that contributes to this activity.
20. *NOAA should consider the societal needs for air quality prediction from an environmental justice perspective*.

Stakeholder engagement

21. *NOAA should develop a paradigm for addressing air quality predictions in a changing climate*. Go beyond the research and figure out how to work with the

stakeholders to equitably meet community needs and provide usable information in a usable form, either alone or (preferably) with other Federal Agencies contributing to this effort. For example, NOAA could lead an annual stakeholder meeting with other agencies such as EPA, USDA, NASA, NIST, and DoE. Extra steps should be undertaken to include traditionally marginalized communities.

NOAA has the mandate and capability to contribute significantly to the nation's understanding of air quality and its impacts, particularly in a changing climate. The SAB and its Climate Working Group believe implementing the report's recommendations will enable the agency to meet the needs of multiple stakeholders for air quality information as the country mitigates and adapts to changes in climate.

Appendix

Climate Change Effects on Air Quality

Many studies have shown that the changes occurring in the Earth's climate will lead to increasing concerns about air quality (e.g., Lin et al., 2008a,b, 2014; Jacob and Winter, 2009). Warmer temperatures (USGCRP, 2017, 2018; IPCC, 2021), including more extremely warm days (e.g., Zobel et al., 2017), and changing weather patterns, including increased stagnation (Leung and Gustafson, 2005; Horton et al., 2014), altered frequency of weather fronts (Turner et al., 2013), more frequent heavy rain events (Janssen et al., 2014; Zobel et al., 2018), and changing emissions from vegetation and human sources (Heald et al., 2008; Lam et al., 2011) will all affect future levels of ozone and particulate matter (PM), two critical current concerns in determining air quality. In addition, more frequent and prolonged droughts would lengthen the wildfire season, resulting in more extensive and intense wildfires and increased dust emissions in some areas. The climate effects on air quality studies also show that the projections of human-related emissions significantly affect future levels of ozone and PM. The resulting increase in concerns about air quality is often referred to as a "climate penalty" on air quality (e.g., https://public.wmo.int/en/our-mandate/focus-areas/environment/air_quality/wmo-air-quality-and-climate-bulletin-no.2). It has been argued that dealing with water issues that emerge from climate change (Ravishankara et al., 2012) and shown in the figure below.

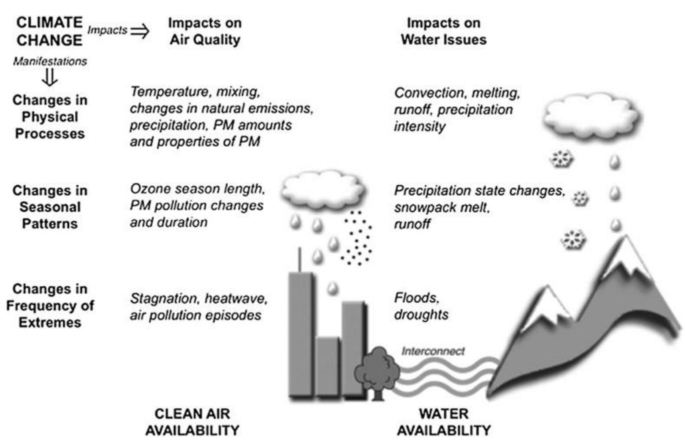

Figure S1: A schematic of the analogy between the impacts of climate change on water and air quality. From Ravishankara et al. 2012.

The energy and transportation sectors, which include energy production, conversion, and use, account for 84% of the U.S. emissions of the radiatively important gases, e.g., carbon dioxide (CO_2), methane (CH_4), and other gases driving climate change. But these sectors also account for 80% of the emissions of NOx that lead to ozone production and facilitate PM production, and 96% of sulfur dioxide, the primary precursor of sulfate aerosol (an important component of PM) (USGCRP, 2018; EPA, 2016, 2017). With energy use worldwide still heavily dependent on fossil fuels, similar percentages are found in many other countries. As a result, mitigation policies to reduce climate change would also considerably lower emissions of PM, ozone and PM precursors, and other hazardous pollutants, reducing the risks to human health from air pollution (Sanyal and Wuebbles, 2022).

The common origins of climate and air quality-related emissions allow for designing win-win options and avoiding win-lose options in decisions. The magnitude of air quality co-benefits from climate mitigation depends on several factors. Countries or regions with higher levels of air pollution have more potential for air quality co-benefits compared to areas where emission controls have been enacted and air pollution levels have been reduced. Different approaches to climate mitigation also yield other reductions. For example, diesel vehicles emit less radiatively important gases than gasoline-powered vehicles per mile. Still, without correctly operating pollution-control devices, diesel vehicles emit more particles and ozone precursors and thus contribute more to air quality human health risks (USGCRP, 2018).

A reduction in future climate changes could also reduce the concerns about air quality from wildfires and windblown dust storms. Wildfire smoke, primarily through the production of atmospheric particles, degrades air quality, increasing the health risks to tens of millions of people in the United States and many more worldwide. Climatic changes, including warmer springs, longer summer and dry seasons, and drier soils and vegetation, have lengthened the wildfire season and increased the likelihood of dust storms (IPCC, 2013; USGCRP, 2018). As a result, we are currently seeing an increasing incidence and extent of wildfires (USGCRP, 2017, 2018; IPCC, 2021). Now, wildfires are viewed as a natural source and not subject to control measures – yet they can become a significant source of future air quality problems (David et al., 2021). The same applies to windblown dust arising from natural processes and human activities.

Reductions in aerosols (or particulate matter, PM) benefit human health. However, reducing aerosols will enhance climate change (e.g., Murphy and Ravishankara, 2018), and it is equivalent to continued accumulation of CO_2 (e.g., Kloster et al., 2010). However, if only light-absorbing black carbon aerosol were cut, there would be positive benefits to both air quality and climate; unfortunately, it is difficult to only reduce black carbon aerosol without concomitant reductions in the light-scattering aerosols.

Outdoor air pollution is estimated to cause over 4 million premature deaths per year worldwide, with most being attributed to particulate matter < 2.5 µm in diameter ($PM_{2.5}$). Currently, the effect of aerosols on human health is calculated by their size and mass, primarily $PM_{2.5}$. When the composition of the particles, particularly their oxidizing capability, is conclusively linked to specific health effects, the oxidative potential may be a better indicator of the health effects of pollution. NOAA, which has significant capabilities in analyzing aerosol composition, must plan for such an outcome as studies (e.g., Daellenbach et al. (2020) and the references therein) suggest such links.

We will first describe the sources of emissions due to climate change and human activities, followed by discussions of the interactions between meteorology and air quality now and in the future with climate change. Finally, we discuss the modeling frameworks within NOAA that can address these issues.

Changes in emissions due to climate change

Wildland Fires

Wildland fires pose a growing threat to air quality and human health. (NAS Wildfire workshop report, 2022). Although wildfires are part of the natural ecosystem cycle in the western United States, it has been increasing at an alarming rate in recent decades, largely a result of anthropogenic warming (e.g., Seager et al. 2015; Abatzoglou and Williams et al. 2016; Williams et al. 2019; Zhuang et al. 2021). For example, the wildfire-burned area over the western U.S. doubled from ~1.69 million acres during 1984-2000 to ~3.35 million acres in 2001-2018. The estimated total cost of wildfires in California in 2018 was $126.1-192.9 billion, mainly attributed to public health degradation from poor air quality (Wang et al. 2020). Extreme droughts and heat waves further intensify wildfires. For example, tens of millions of trees died during the 2012–2016 California drought, creating a massive fuel load for wildfires [*Goulden and Bales*, 2019]. During the 2020 fire season in California, back-to-back large summer heat waves, punctuated by dry spells, made conditions ideal for the August Complex and Creek Fires, the first and fifth largest wildfires in California's history. Over the southwestern U.S., the total burned area in 2020 jumped to more than five times that in 1984-2000 (~8.8 million acres). Such rapid increases in wildfires become a major threat to lives, property, and local and regional economies and an increasingly widespread and dominant source of air pollution. More importantly, it has turned the vast wildlands of the western U.S., where air used to be pristine, into an important source of air pollution, both regionally and nationally. For example, in the summer of 2021, smoke from California wildfires was transported across the North American continent, all the way to its east coast. Drought and heat waves increase smoke emissions, intensify air stagnation and dryness, weaken pollution dissipation, and prolong its lifetime in the atmosphere.

To cope with and mitigate the impact of such rapid intensification of wildfires and its compounded effect on drought and heatwaves, there is an urgent societal need for integrated information on wildfire and climate, especially drought and heatwaves. For example, the U.S. Forest Service Wildland Fire Assessment System (WFAS) uses real-time drought and temperature information provided by NOAA to assess wildfire risk. The National Integrated Drought Information System (NIDIS) established the Drought and Wildland Fire Nexus (NDAWN) initiative in 2015 to improve drought information and communication with fire management communities. Hence, the interaction between droughts, heatwaves, and wildfires and their compounding effect must be considered to improve understanding, modeling, and prediction/projection of air quality in a changing climate.

Some of the existing challenges include the following:

- The impacts of drought and heat waves on wildfires and their compounded effect on air quality are poorly understood. This poor understanding arises partly because there have been too few observed examples to identify their shared origins and model their co-occurrences in statistically robust ways. It is further exacerbated by a lack of integrated studies on how physical and biological climate processes affect air pollution. In addition, many of the processes underpinning the impact of these extreme climate events on air pollution are also not represented well, if at all, in the climate and air quality models. For example, how do climate and vegetation conditions affect fire plume height, chemical composition, lifetime, and long-range

transport of fire emissions? There are also complicated interactions between climate, land conversion, and wildfire management (e.g., Kloster et al., 2012
- Numerous barriers exist among disciplines and between researchers and decision-makers in the study and risk management of drought–heat wave–wildfire events. The two groups view problems from their respective perspectives. For example, scientists build their reputation on the thoroughness of their work, especially on understanding the limitations and uncertainty in their results. As such, they are reluctant to advocate for imperfect solutions. In contrast, risk managers are accustomed to working with imperfect (but timely) information to save lives and manage the impacts of hazards (*Fu et al. 2021*). Reconciling these differences is central to supporting NOAA's priority on Climate Ready Nation. In particular, NOAA needs to focus on how to provide scientifically sound, though imperfect, climate and air quality information and early warnings.

Changes in the emissions of biogenic volatile organic compounds (BVOC) change ozone concentrations and secondary organic aerosols contributing to degrading air quality. Even in polluted areas, changes in BVOC are projected to impact air quality substantially (Liu et al., 2019). In addition, BVOC production increases with higher CO_2 and temperature, enhancing the feedback (Sporre et al., 2019).

Responses of desert and agricultural dust to human land use and climate changes

Desert dust on the regional scale can have large responses related to changes in climate. For example, a 4-fold change in dust transported from North Africa to Barbados correlated with changes in precipitation ((Prospero and Lamb, 2003). In the U.S., regional-scale changes in climate and land use are thought to have driven the 'dust bowl' during the 1930s, resulting in catastrophic dust events (Cook et al., 2008) with enormous consequences to the nation. Projecting such changes in the future is difficult to assess because of the complexity of drivers of changes in dust from land use, land cover change, water use as well as climate (e.g., in the United States, examples include Reheis (1997); Okin and Reheis (2002); Lawrence and Neff (2009)). Future projections of desert areas are highly sensitive to the ability of semi-arid vegetation to deal with water stress under higher CO_2 conditions (e.g., assumptions about CO_2 fertilization (Mahowald, 2007)). Projections using CMIP5 models suggest desert areas should contract over much of the globe, except near the Mediterranean, despite decreases in precipitation over the same regions (Mahowald et al., 2016). Assumptions about plant physiology change vegetation response in climate projections, determining whether climate change will cause increased or decreased desert areas (Zarakas et al., 2020).

Increases in pollen in a warmer world

There is growing evidence that the number of pollen pollution days is increasing with climate change. (see https://www.epa.gov/climate-indicators/climate-change-indicators-ragweed-pollen-season, and references therein) The increases are larger at higher latitudes than lower latitudes, consistent with larger warming at higher latitudes. Pollens are responsible for allergies (asthma) and increased hospital visits. Therefore, it is important to consider pollen in dealing with air quality in a changed climate. Other potential influences of increased pollen (e.g., acting as ice nuclei) on the climate system are still unclear.

Meteorology, climate, and air quality interactions.

There are clear relationships between weather and air pollution conditions for ozone and particulate matter. For ozone, warming temperatures often lead to higher ozone, partly due to higher natural isoprene emissions (Brown-Steiner et al., 2015). In addition, changes in the Brewer-Dobson circulation may lead to more ozone being transported into the troposphere (Hegglin and Shepherd, 2009). For both ozone and PM, changes in stagnation rates under warmer temperatures are likely to be significant under climate change (Jacob and Winner, 2009; Liao et al., 2006); Liao et al., 2006). Other changes in transport patterns under climate change are usually much less critical than emission changes (Sun et al., 2019).

Transboundary pollution transport.

Even though the whitepaper is focused on U.S. air quality, it is imperative to consider what happens outside the territorial boundaries because they influence, or can influence, air quality within the United States. Such interactions occur relative to "neighboring regions" such as Canada and Mexico and from faraway places such as Asia. This whitepaper notes these issues and suggests what new measurements and modeling would enhance this prediction/forecasting capability and position the United States for better resilience. Many other ongoing efforts within NOAA examine different features of transboundary transport. Since air quality-related research aims to improve information products, looking at the modeling framework within NOAA is essential. It is important to note that the US and its territories extend over a vast part of the northern hemisphere and are close to other countries in the hemisphere.

Air quality predictions and predictability.

ECMWF and NASA include forecasts of aerosols in their routine assimilations, at least in the research mode, but it is not clear that their sub-seasonal aerosol predictions are of good quality (Gelaro et al., 2017; Zuidema et al., 2019; Kok et al., 2021). ECMWF has preliminary evidence that including aerosols in the model improves the sub-seasonal predictability of the physical weather system, but this does not show that the aerosols themselves have quality (Benedetti and Vitart, 2018). While modeling the daily dust and other aerosols for decades has shown some skill in individual events (Mahowald et al., 2002; Grousset et al., 2003), sub-seasonal to seasonal scale hindcasting or forecasting has not been shown. Hindcasting variability in past dust interactions suggests that the models generally lack skill in seasonal dust variability, except in large regions like North Africa (Smith et al., 2017). However, large-scale climate fluctuations, like NAO or El Nino, could provide some ability in sub-seasonal to seasonal forecasts in some regions (Luo et al., 2002; Moulin and Chiapello, 2004; Okin and Reheis, 2002).

Planetary Boundary Layer (PBL) Processes and Air Quality

Air quality is essentially a boundary layer issue (emissions mainly occur in this region, people live there, and other impacts such as visibility are important for this region). Therefore, enhancements in boundary layer science, modeling, observations, and processes are needed to improve forecasts/predictions of air quality.

The PBL is the lowest layer of the atmosphere and forms the interface between the surface and the free troposphere. PBL height is critical for determining the concentration of pollutants in the lowest part of the Earth, where it affects public health. In addition to mixing chemical constituents, the PBL regulates carbon, energy, weather, and water vapor in the lowest part of the Earth system. PBL is a challenge as it varies diurnally, geographically, and seasonally and is affected by climate. It can be as low as a few meters in the cold tundra and cryosphere and as high as 5 km in the hot deserts. Measurements of water vapor and temperature are helpful in determining the height of the PBL and modeling chemical processes, including, for example, the oxidation of gaseous SO_2 to produce sulfate particles and the hygroscopic growth of particles both of which play vital roles in particulate matter (PM) concentrations in the lowest part of the atmosphere.

The height of the PBL and corresponding ventilation coefficients in models play vital roles in the skill of air quality models. Recommendations to develop an observing system that improves the estimates of PBL globally and over challenging conditions, including (i) unstable, non-homogenous, and non-stationary PBL (ii) PBL under cloud cover; (iii) PBL over complex terrain, will have significant benefits for air quality modeling and forecasting. Sub-seasonal to seasonal forecasting of the PBL height is an achievable goal with a moderately long (decadal) measurement record. The improved estimation of the PBL will allow for proper accounting of diurnally resolved mixing between the PBL and the free troposphere in air quality models, improving the skill of these models and advancing the community towards 2-to-3-day air quality forecasting capability. We note that PBL is essential for air quality predictions and many topics (e.g., weather prediction and climate change) that fall under NOAA's mandate.

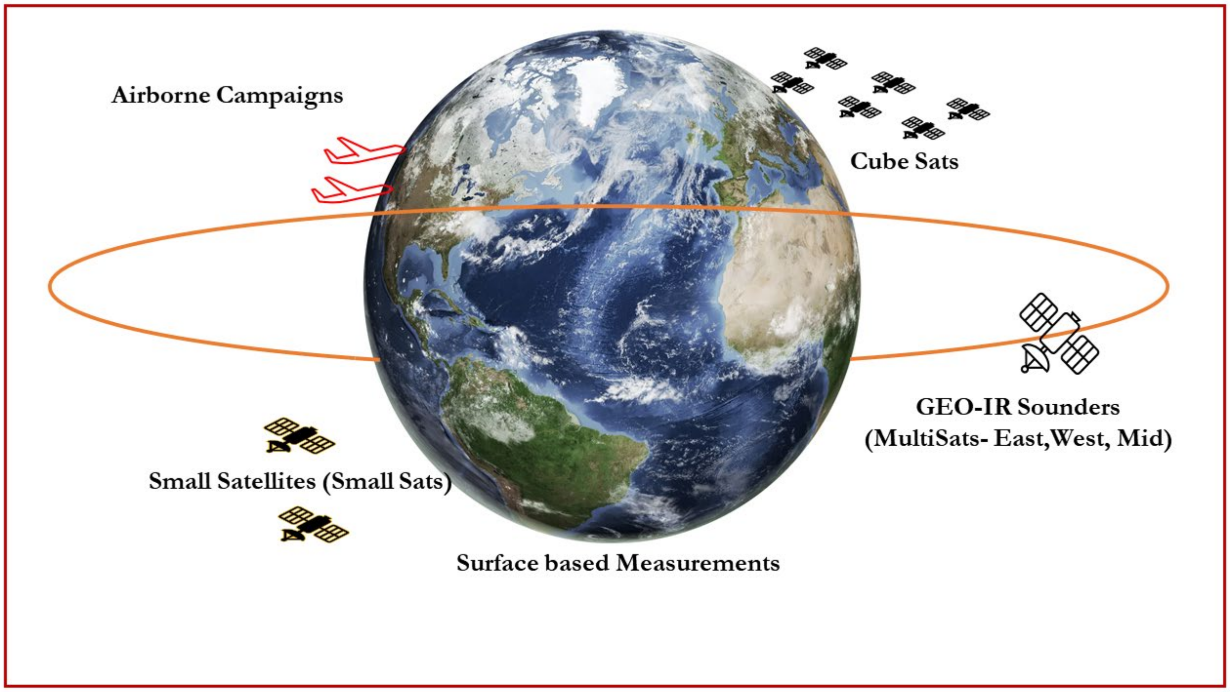

Figure S2. Notional Multi-Platform Observation System for the Planetary Boundary Layer

Air temperature and water vapor profiles in the PBL are typically measured by limited weather stations in developed countries using ground-based measurements and a small number of sondes. The global record is woefully patchy in space and sporadic in time. An effort involving several countries and modeling agencies, led by NOAA, to craft a strategy involving a constellation of geostationary satellites, multiple low-cost cubes, small satellites, airborne campaigns, and ground stations to fill many gaps in these observations is needed. Observations of variables in the PBL call for a multi-platform approach using surface-based measurements, airborne campaigns, satellite-based measurements, and several small free-flying CubeSats and SmallSats. Similar to the approach taken by the air quality constellation of geostationary sensors in the western hemisphere (TEMPO), eastern hemisphere (GEMS), and middle hemisphere (SENTINEL IV), a PBL constellation (Shown in Figure S2) is needed to close the gaps in the current measurements. Such an effort requires international collaborations to build instruments on geostationary platforms making uniformly calibrated and like measurements to enable the development of a global PBL temperature, height, and water vapor product. Geostationary I.R. sounders from JAXA, EUMETSAT, and NOAA already exist; however, the data from these sensors are not optimized for uniform and like observations of PBL thermodynamic variables. The international community should design coordinated high spatial and temporal measurements of these variables using preferably the same instruments. These measurements should be supplemented by several polar-orbiting SmallSats and CubeSats outfitted with lidars, radars, hyperspectral I.R. sounders, and microwave sounders to provide (1) vertically resolved observations in the PBL of water vapor, temperature, and aerosols and (2) validation of Geostationary I.R. measurements and (3) as a means of gap filling where the is no coverage from the Geostationary sounders. Global Positioning System radio occultation (GPS-ro) can also provide global PBL heights (Ao et al., 2012).

Because GPS-ro operates in the L-band frequencies (1565 nm to 1625 nm), clouds and precipitation do not affect its signals.

Atmospheric dynamics, pollutant transport, chemical reactions, and atmospheric composition are strongly coupled in the planetary boundary layer (PBL). Their integration for modeling environmental impacts, climate change, weather forecasts, and air quality are among the most urgent needs of the air quality community. Parameterization of the planetary boundary layer (PBL) processes in meteorological models play a direct and significant role in predicting the dynamics of pollutants (Pérez et al., 2006, Cuchiara et al., 2014). A starting point for this challenge is global observations of the PBL. On a global scale, satellite observations of thermodynamically relevant variables in the PBL, namely water vapor and temperature, have advanced (e.g., the Atmospheric Infrared Sounder, AIRS). Still, they lack the temporal and vertical resolution necessary for air quality modeling. AIRS vertical resolution for water vapor is 2.7 ± 1 km between 600 and 1,000 hPa (Maddy & Barnet, 2008) and approximately 1 km for temperature in the lower troposphere.

In this report, we will limit ourselves to recommendations to improve correct estimates of PBL heights and variables important for air quality, such as temperature and relative humidity, to close gaps in these measurements from the current airborne, ground, and space-based observations. Current PBL observations – both passive and active sensing from space, do not provide measurements in the PBL at temporal and spatial resolutions needed to address key PBL science and applications questions and the needs of the modeling community. We, therefore, recommend designing the next generation of sensors with spatial and temporal resolution requirements that will address these questions.

Urban-Rural Interface and Interactions

In the United States, air quality is often considered primarily an urban issue that harks back to the LA smog days. However, non-urban areas play essential roles in the air pollution of adjacent or nearby urban areas. Ammonia from agriculture and hydrocarbons from fossil fuel extraction in rural areas are two significant emissions contributing to urban (and rural) air quality degradation.

The feedlots and other agricultural activities are the primary sources of ammonia. The combination of ammonia with nitric acid from urban NOx emissions contributes to ammonium nitrate PM enhancements, especially when the temperatures are low enough to sustain such PM. One of the prominent enhancements is the brown clouds of the front range in Colorado. Similar issues have recently hampered air quality in California's South coast air basin.

Fossil fuel extraction, especially the recent fracking activities, has enhanced reactive hydrocarbon emissions. These hydrocarbon increases enhance ozone through photochemical processes and also lead to secondary organic aerosols that contribute to PM.

Another significant concern is the increased wintertime ozone in some areas. These ozone formation events in winter can extend the ozone pollution season to winter. Similarly, some areas, such as Salt Lake City and its surroundings, have enhanced ozone and PM pollution in winter, as noted earlier. Therefore, researching and quantifying ozone and PM formation in winter is essential for NOAA. Answering the questions about how the air quality will be altered in the future climate via these unusual processes is worthy of attention.

A Modeling Framework

The current state of NOAA modeling effort as it relates to air quality.

The Unified Forecast System (UFS) weather model is a community model that can be integrated into atmosphere-only models or coupled with a set of components in the UFS repository. It is intended for short (sub-hourly to two days) to seasonal forecasts. Current efforts to model air quality dynamically couple the Community Multiscale Air Quality CMAQ model to the UFS weather model. The UFS weather model includes the Goddard Chemistry Aerosol Radiation and Transport model (GOCART) and has an application goal to forecast aerosols "out to several days."

Air quality and wildfire predictability research and potential operational forecasts beyond "several days" will require a model to include factors important for air stagnation, wildfire, dust, pollen, etc. Prognostic soil moisture and other aspects of the terrestrial biosphere important for these applications will be needed. The UFS has the components under development, but research is required to evaluate them.

The Unified Forecast System (UFS; Jacobs, 2021) is a community-based, coupled, comprehensive Earth system model with applications that span local to global domains and predictive time scales from sub-hourly analyses to seasonal predictions. It is designed to support the weather enterprise and to be the source for NOAA's operational numerical weather prediction applications. The UFS atmospheric model has numerous subcomponents, including the Finite-Volume Cubed-Sphere (FV3) dynamical core and the Common Community Physics Package (CCPP). These components encompass a library of physical parameterizations (the CCPP Physics) and an infrastructure to connect it interoperably to host models (the CCPP Framework; Heinzeller et al., 2022). Currently, the only operational configuration of the UFS that accounts for atmospheric composition and chemical processes is a member of the Global Ensemble Forecast System (GEFS) that uses GOCART bulk aerosol modules (GEFS-aerosol). Developmental versions of the UFS include aerosol and chemistry processes represented via the CCPP and the Community Mediator for Earth Prediction Systems (CMEPS). This development aims to predict atmospheric composition for global and limited-area applications and eventually replace operational systems such as the smoke configurations of the Rapid Refresh (RAP) and High-Resolution Rapid Refresh (HRRR) systems used for predicting the impacts of wildfires. Additionally, NOAA is developing a replacement for the currently operational National Air Quality Forecast System, in which meteorological fields are used to drive CMAQ offline. This innovation will use an online system in which CMAQ is directly coupled to the UFS atmospheric model for regional applications.

GFDL's AM4.1, the atmospheric component of the GFDL-ESM4 Earth system model, includes interactive tropospheric and stratospheric gas-phase and aerosol chemistries. The bulk aerosol scheme includes 18 transported aerosol tracers to represent sulfate, nitrate, ammonium, dust, black carbon, organic carbon, and sea salt. AM4.1 has an online representation of gas-phase tropospheric and stratospheric chemistry. The combined tropospheric and stratospheric chemistry scheme includes 59 prognostic and 41 diagnostic gas-phase chemical tracers, with 43 photolysis reactions, 190 gas-phase kinetic reactions, and 15 heterogeneous reactions. The sulfate production can also be calculated with a simplified version using prescribed ozone and radicals (AM4.0), where $SO_4^{=}$ is assumed to be neutralized into ammonium sulfate. Optical properties (mass extinction coefficient, single scattering albedo, asymmetry parameter) are calculated offline using Mie theory for multiple wavelengths, and relative humidity for hygroscopic aerosols.

Given these models and their development, air quality predictions will test the modeling system and provide operational information. Further developments of the models will be critical to a successful integrated model that can predict air quality from days to weeks and project air quality on seasonal to decadal timescales. Such an effort is essential in the context of earth system predictability to meet the needs of the nation in the 21st century.

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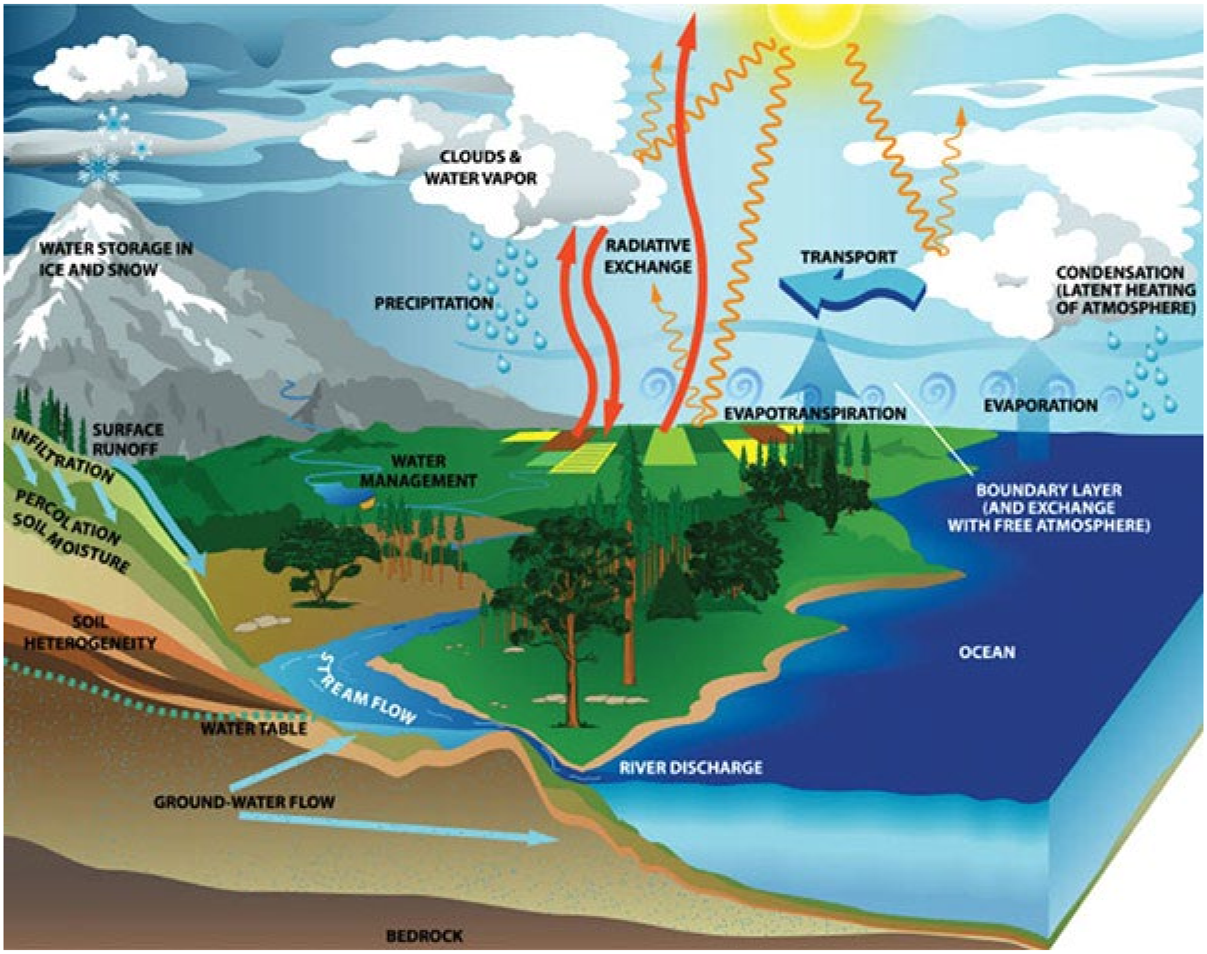
Figures



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