Summary Report of the Review of the NOAA Chemical Sciences Laboratory

23-25 February 2021

Review Panel Members:

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Dr. Belay Demoz, University of Maryland Baltimore County

Dr. Emily Fischer, Colorado State University

Dr. Astrid Kiendler-Scharr, Forschungszentrum Jülich GmbH

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1. Overview

The Chemical Sciences Laboratory (CSL) review was conducted 23-25 February 2021. The review covered CSL research from 2015 to the present under three research themes:

1. Air Quality Research
2. Climate Research
3. Stratosphere Research

Note that after the formal review presentations and discussion in February 2021, and during the review process, the panel agreed to add to the CSL review the overall performance of two additional components:

4. Research Strategy
5. Leadership

Evaluation of these themes was based on the following criteria:

- **Quality:** Assess quality of research over the review period, and whether appropriate approaches are in place to ensure high quality work will be performed in the future.
- **Relevance:** Assess the degree to which research and development is relevant to NOAA's mission and of value to the Nation.
- **Performance:** Assess the overall effectiveness with which the laboratory plans and conducts its research and development.

Each panelist was asked to independently prepare written evaluations of at least two of the three research themes. These evaluations were to include an overall rating for the science as well as ratings and specific comments for the three evaluation criteria listed above. Possible ratings included:

- **Highest Performance** – Laboratory greatly exceeds the Satisfactory level and is outstanding in almost all areas
- **Exceeds Expectations** – Laboratory goes well beyond the Satisfactory level and is outstanding in many areas
- **Satisfactory** – Laboratory meets expectations and the criteria for a Satisfactory rating
- **Needs Improvement** – Laboratory does not reach expectations and does not meet the criteria for a Satisfactory rating. (This rating requires the reviewer to identify specific problem areas that need to be addressed.)

In preparation for the review, panelists were provided guidance on the organization and content of the review as well as access to the review materials, including presentations, StoryMaps, and supporting documents. The review was conducted online using a combination of video and audio web conferencing platforms. The format of the review was well thought out and generally effective considering the physical distance between all the participants. The use of short overview talks followed by group discussions allowed the in-depth investigation of topics of interest to the review panel. The review panel did miss out on one-on-one discussion with staff. In this regard, the review panel, with the help of CSL leadership and administration, hosted an extra group discussion session on 26 February 2021 with all the CSL Early Career Scientists (i.e., those within 10 years of their PhD). Given the challenging circumstances of a remote review format, the review panel felt that the CSL team did as much as they could to accommodate the review panel's needs and provided a complete overview of the lab's accomplishments and workforce that engaged the reviewers in an open and transparent manner. CSL management and staff should receive the highest compliments for the quality and organization of the review.

The presence of higher management from the Office of Oceanic and Atmospheric Research (OAR) throughout the entire review was appreciated by the panel. Their level of engagement and openness facilitated productive discussions with the CSL management team about their strengths and weaknesses. This was critical in helping the panel formulate constructive comments and recommendations that are committed to preserving CSL's outstanding level of international impact and success into the future.

The remainder of this report summarizes the panel's ratings and comments. This includes high level findings and recommendations relevant to the entire lab as well as specific to each theme. This report does not represent a consensus but serves as a summary of individual reviewer reports. Nevertheless, it can be said that the individual assessments contain no information regarding high level comments or recommendations that could be considered inconsistent or contradictory.

2. Summary of Laboratory-Wide Findings and Recommendations

When viewed as a whole, CSL has earned the rating of Highest Performance.

2.1 Individual Panelist Ratings

The overall summary rating for CSL of Highest Performance is consistent with the individual ratings of the panel members provided in the table below.

Reviewer	Rating Categories	Air Quality	Climate	Stratosphere	Research Strategy	Leadership
Lefer	Overall Quality Relevance Performance	Highest Performance Highest Performance Highest Performance Highest Performance	Highest Performance Highest Performance Highest Performance Highest Performance	Highest Performance Highest Performance Highest Performance Highest Performance	Highest Performance	Highest Performance
Demoz	Overall Quality Relevance Performance	Highest Performance Highest Performance Highest Performance Exceeds Expectations	Highest Performance Highest Performance Highest Performance Highest Performance		Highest Performance	Exceeds Expectations
Fischer	Overall Quality Relevance Performance	Highest Performance Highest Performance Exceeds Expectations Highest Performance	Highest Performance Highest Performance Highest Performance Exceeds Expectations	Highest Performance Highest Performance Highest Performance Highest Performance		
Kiendler-Scharr	Overall Quality Relevance Performance	Highest Performance Highest Performance Highest Performance Highest Performance	Highest Performance Highest Performance Highest Performance Highest Performance		Highest Performance	Highest Performance

Maycock	Overall Quality Relevance Performance	Highest Performance Highest Performance Highest Performance Highest Performance	Highest Performance Highest Performance Highest Performance Exceeds Expectations	Highest Performance Highest Performance Highest Performance Exceeds Expectations	Highest Performance	Exceeds Expectations
Newman	Overall Quality Relevance Performance	Highest Performance Highest Performance Highest Performance Highest Performance	Highest Performance Highest Performance Highest Performance Highest Performance	Highest Performance Highest Performance Highest Performance Highest Performance		
Pierce	Overall Quality Relevance Performance	Highest Performance Highest Performance Exceeds Expectations Highest Performance	Highest Performance Highest Performance Highest Performance Exceeds Expectations	Exceeds Expectations Exceeds Expectations Exceeds Expectations Exceeds Expectations	Highest Performance	Highest Performance

The overall lab rating is further justified and substantiated by the summary findings.

2.2 Panel Summary Findings

Summary Finding #1: CSL is continuing its historically strong role in conducting science on the forefront of air quality, climate, and stratosphere research. Critical factors to this success have been:

1) The quality of the personnel in the laboratory, many of whom are internationally recognized experts. This is evidenced by the numerous awards, prolific participation in international assessments, leadership in national and international organizations, service on editorial boards for an array of high-quality scientific journals, and an outstanding peer-reviewed publication record.

2) Freedom to define scientific research to respond to changing scientific priorities. This is evidenced by the shifts in the balance of work and scientific emphasis from stratospheric ozone to climate, air quality, and Earth's radiation budget over the past two decades. Interestingly, the lab is poised to take a renewed leadership in stratospheric chemistry over the next decade.

3) Local control of resources and their application to emerging opportunities. The ability to budget, organize, and direct science within CSL enables its scientists to recognize and respond to urgent needs in a way that is not possible for other organizations. A prime example is the recent comprehensive COVID Air Quality Study observations. Other examples include airborne field work to quantify and understand wintertime air quality in the U.S. as part of the Wintertime Investigation of Transport, Emissions, and Reactivity (WINTER) and Utah Winter Fine Particulate Study (UWFPS) field campaigns.

4) Pursuit of science that addresses important knowledge gaps. CSL is committed to ensuring that critical knowledge gaps receive the attention that they deserve. An excellent example is how CSL and its partners designed innovative experiments to better understand Volatile Chemical Products (VCP) emissions in the US and Europe. The Laboratory's commitment to developing instrumentation and designing effective field campaigns on the ground and in the air have been groundbreaking and define the current state of knowledge. Other examples of CSL working to close knowledge gaps include the recognition that the community lacked a global database of tropospheric ozone (i.e., Tropospheric Ozone Assessment Report, TOAR) and the persistent multi-year focus to understand the emissions, transport and processing, and impacts of wildfires.

5) Leadership through interaction with stakeholders, collaboration building, and contributions to national and international assessments. A prominent example is the FIREX-AQ field campaign which was a collaboration with NASA and was conducted with numerous partnering agencies (National Science Foundation, U.S. Forest Service, Joint Fire Science Program, Bureau of Land Management, National Interagency Fire Center, California Air Resources Board, and Environment & Climate Change Canada). Other examples include the commitment from CSL scientists to take prominent leadership roles in the writing of the World Meteorological Organization (WMO) Ozone Assessment Reports, the Fourth National Climate Assessment (NCA4), and TOAR. The WMO Ozone Assessments and NCA4 have direct routes into policy making and are vital channels to feed the latest science through to governments. The findings of the first TOAR highlighted the importance of tropospheric ozone to climate change and the need to do a better job of retrieving and comparing tropospheric ozone records from different satellites.

6) Development of technologies that enable new measurements and wider proliferation of key observations. CSL scientists developed unique instrumentation such as the aircraft-deployable Laser Imaging Nephelometer, which provides in situ measurements of light scattering at fixed angles and provides fundamental information needed to validate satellite aerosol optical depth retrievals. Other examples include CSL's new measurements of stratospheric aerosols using the Portable Optical Particle Spectrometer (POPS) instrument that are critical for Stratospheric Aerosol and Gas Experiment III (SAGE III) validation and assessing the impacts of pyrocumulus black carbon and volcanic sulfur dioxide (SO_2) on stratospheric chemistry. Similarly, the high-quality observations from the new CSL SO_2 laser induced fluorescence (SO_2-LIF) instrument with ~1 pptv detection limit was able to demonstrate that cross tropopause SO_2 transport is not a significant source of stratospheric aerosol mass. These in situ measurements have helped to resolve discrepancies in satellite retrievals of lower stratospheric SO_2 and provide more confidence in climate model predictions. Incidentally, the development and commercialization of the POPS instrument is a great example of lab innovation leading to a much wider impact on the atmospheric chemistry research field.

Summary Finding #2: The demographics of CSL is grossly imbalanced with a lack of gender and racial diversity. The CSL federal workforce is grossly imbalanced with only 5 female scientists (19%) while the University of Colorado – Boulder (CU-Boulder) Cooperative Institute for Research in Environmental Sciences (CIRES) workforce is better with approximately 19 female scientists (33%). Both workforces are also overwhelmingly white, 92% and 84% for federal and CIRES, respectively. That these imbalances extend to the CIRES workforce creates a challenge for growing the federal workforce as the CIRES pool of scientists expect to compete for federal positions, yet they do not represent an adequate cross section of applicants for correcting these demographic problems. It should also be noted that the average age for the federal workforce at CSL is approximately 54 years old, and only two employees are under the age of 40. It is important to note that at least 16 of the CSL staff are over 65 years old, and another 22 are over 55 years old. This data suggests that with a persistent goal of actively recruiting more diverse scientists, CSL should make considerable progress over the next decade.

2.3 Panel Summary Recommendations

Panel Summary Recommendation #1: CSL needs to improve the diversity of its leadership and staff. CSL should consider setting specific goals for the hiring of women and minorities, along with procedures to make sure that these issues are fully considered in any hiring decisions. Awareness training for gender and other bias should also be required for all personnel. Given the severe lack of diversity within CSL and the slow progress to address this issue over the past 5 years, CSL should expand opportunities for entry into the organization. In addition, CSL should establish mentoring programs based on best-practices to ensure that all aspects of diversity, but especially racial diversity, are supported. CSL should also recognize that the current level of diversity itself signals a problem. It is essential that CSL also evaluate its workplace climate with the goal of uncovering and addressing exclusionary or hostile environments/attitudes/beliefs that appear to be interfering with CSL making meaningful progress to address this important issue. Given the current age of the workforce and anticipated retirements, hiring strategically over the next decade could make a significant step towards correcting this imbalance.

Panel Summary Recommendation #2: The CSL Research Strategy which encourages a high level of integration between field campaigns, laboratory studies, modeling, and instrument development across all research foci leads to outstanding research and should be actively nurtured and maintained. CSL's integrated research approach, with a continuous cycling of instrument development, laboratory studies, field campaigns, and modeling, is highly effective and adaptable. This research strategy has been the cornerstone of CSL's research for decades and has demonstrated success through effectively using results from each stage of the research cycle and building upon it to advance the science at a national and international level. At the heart of this strategy is an integrated research approach that equally relies on laboratory studies, field campaigns, modeling, and instrument development. Over the years, this fundamental research strategy has become central to the Laboratory's culture and has successfully addressed CSL's core science goals while also revealing a surprising number of significant and unanticipated discoveries.

Panel Summary Recommendation #3: NOAA OAR should continue to entrust CSL leadership with the management of the Laboratory's research funds and scientific direction. CSL should be considered a treasure worthy of protection. It is a uniquely effective and innovative organization. CSL management and staff have demonstrated the effectiveness and flexibility of the present decision-making model. Stable base funding empowers the laboratory to perform research independently, which is of enormous importance in the sometimes challenging environment in which drafting and maintaining environmental policies takes place.

3. Findings and Recommendations by Thematic Area

3.1 Air Quality Research: The Air Quality programs at CSL have a long history of leading the US in studying emissions of photochemical precursors and products, their impacts at local and regional scale, and the associated contributions to regional scale air pollution and climate forcing.

3.1.1 Quality of Air Quality Research

CSL has led research on several air quality topics over the last 5 years. Key research areas include the emissions from nontraditional oil and gas development, fundamental chemistry underlying wintertime air pollution episodes in U.S. cities, emerging sources of urban air pollutants, the composition and chemical evolution of wildfire smoke, and the impact of COVID-19 on air pollution abundances. In each of these topic areas, CSL has 1) contributed to new instrumentation/techniques to collect the most chemically detailed measurements possible, and 2) directly tackled policy-relevant questions. CSL is an irreplaceable national treasure in terms of its instrumental capabilities and scientific expertise.

Finding: CSL is a national and international leader in design, development, and deployment of high quality, high precision, and high temporal sampling instruments designed to measure atmospheric composition. These measurements are used to evaluate the accuracy of air quality model emissions and photochemistry predictions during intensive field campaigns and have resulted in several recent important discoveries of previous unknown compounds and/or processes.

Finding: CSL has contributed to the improvement of air quality in the United States through its efforts to 1) evaluate and improve the underlying emissions inventories, and 2) develop, through process-based field and laboratory investigations, improved descriptions of the photochemical mechanisms that lead to air quality degradation. During the previous 5 years, CSL scientists deployed several instruments onboard the NASA DC-8 aircraft as part of the NASA 2016-2018 Atmospheric Tomography Mission (ATom) Earth Venture Suborbital (EVS-2) mission. These measurements contributed to an improved understanding of global O_3 distribution and sources and contributed to international data bases of ozone in the remote troposphere. CSL scientists played a leading role in the recent NASA/NOAA Fire Influence on Regional to Global Environments Experiment - Air Quality (FIREX-AQ) field campaign and led the FIREX FireLab 2016 experiment. Similarly, the detailed laboratory measurements of wildfire emissions, and subsequent verification of these measurements in the field, has provided unprecedented new information on wildfire behavior and made significant contributions to national and international fire research, databases, and programs. It is also important to note that the particular care CSL scientists take to calibrate and intercompare their measurements is impressive and explains why they are a trusted source of information in our field.

Finding: CSL scientists' retrospective analysis of raw mass spectra data collected during the 2010 California Nexus Research at the Nexus of Air Quality and Climate Change (CalNex) field campaign led to the discovery that volatile chemical products (VCPs), exceed motor vehicles as urban volatile organic compound (VOC) emission source. This discovery has been corroborated with measurements conducted in New York City during 2018 and forms the basis for the next major CSL field campaign, Atmospheric Emissions and Reactions

Observed from Megacities to Marine Areas (AEROMMA), which is planned for 2023. This end-to-end capability, from formulation, instrument design, deployment, and utilization of the measurements to improve our understanding of regional and global air quality is something that CSL excels at and demonstrates the highest quality research.

Finding: The Laboratory's impressive set of high impact air quality publications and new world class air quality modeling components are a good indicator of the CSL's high quality. CSL civil servant scientists and their CSL colleagues within CIRES publish high impact manuscripts in peer reviewed journals that often guide and impact the direction of new research within the air quality community.

3.1.2 Relevance of Air Quality Research

Finding: CSL Air Quality research is highly relevant to NOAA's mission and of value to the Nation. The active engagement with air quality management is a key component of CSL's end-to-end capabilities in air quality research. CSL field campaigns are designed to address specific needs of national and regional air quality management agencies. Stakeholders include the oil and gas industry, the petrochemical industry, state level air quality regulators, and federal agencies such as the U.S. Environmental Protection Agency (EPA), NSF, and the U.S. Department of Agriculture (USDA). The CSL ability and desire to pursue air quality research that is beneficial to society is particularly noticeable and deserving of praise. The panel appreciated the opportunity to virtually meet and talk with the air quality stakeholders from the State of Colorado and the California Air Resources Board that are engaged with the CSL research enterprise.

Finding: CSL should seek to be actively engaged in any future Air Quality Research Subcommittee (AQRS) activities. CSL staff have provided valuable leadership and organizational infrastructure to the Air Quality Research Subcommittee (AQRS) and helped this group transition to the Air Quality Research Seminars and Discussion (AQRSD) after the AQRS charter expired. The panel is optimistic that the AQRS charter will be renewed later this year and looks forward to air quality scientists at both NOAA and EPA providing strong leadership of AQRS.

3.1.3 Performance of Air Quality Research

Finding: CSL conducts its air quality research and development in an effective and efficient manner. The output of the Laboratory is extremely high in both the actual number of papers and their impact. By all metrics, publication quality and quantity are consistent with a rating of 'Highest Performance'. CSL also demonstrates great effectiveness in making assessments and providing information for stakeholders that use the outcomes of their work.

Finding: CSL is a visionary organization that is leading the Nation in understanding and improving air quality. The Laboratory functions often as an initiator of collaboration in the science community. For example, CSL leadership and vision was the driving force behind successful 2016 FireLab experiments and 2019 FIREX-AQ field campaign. The continued CSL leadership to write an improve TOAR falls in this category. It is both very welcome and well timed that the findings of the first TOAR highlighted the importance of tropospheric ozone to air quality and climate change. TOAR also clearly identifies gaps and deficiencies in our observing system and analysis tools.

Finding: The active interactions between the different components of the CSL air quality research programs reinforce the outcome of each program and should be continued and expanded. A particularly impressive example of holistic integration of CSL research programs was the research related to wildfires and prescribed fire. FireLab measurements informed and helped plan the FIREX-AQ in situ and remote sensing field campaign, which was directly relevant to (and evaluated by) the Rapid Refresh Chemistry (RAP Chem) model.

Finding: CSL has made outstanding contributions to our understanding of air quality, however CSL could do a better job of transitioning their air quality research to modeling applications. CSL should seek to develop better connections between various CSL air quality research and the NOAA Global Forecast System (GFS) and Air Resources Laboratory's (ARL) Operational Air Quality Forecasting team. It would be truly game changing if the fire modeling capabilities of the CSL and Global Systems Laboratory (GSL) High-Resolution Rapid Refresh (HRRR) model could somehow be better and more strongly reflected in the NOAA ARL National Weather Service Air Quality forecast. CSL's numerous recent contributions to our understanding of air quality (e.g., improved fuel-based emissions inventories for NOx, better shale oil/gas emissions, and new knowledge about wintertime pollution) have yet to be fully incorporated into a research forecast model that could influence the "official" NOAA air quality forecast. This weak link in NOAA's Research to Applications/Operations in air quality is a huge, missed opportunity.

3.1.4 Recommendations for Air Quality Research

Air Quality Recommendation #1: CSL research could better integrate environmental justice in considering how to prioritize scientific topics. There are large disparities in the impact of air pollution. CSL has collected some of the best urban air quality datasets for Houston, Los Angeles, and the Colorado Front Range over the past 10 years. As CSL considers and plans its future field campaigns, it would be a considerable service to the U.S. national interest to investigate how their data acquisition could be modified to better document if a particular group of people are bearing a disproportionate share of unhealthy/poor air quality.

Air Quality Recommendation #2: CSL scientists should continue to play an active role in defining the components and preparing for NOAA's Geostationary and Extended Orbits (GEO-XO) satellite system. While CSL scientists are already playing a leadership role in defining the atmospheric composition component of GEO-XO satellite system, CSL should expand their role in design and implementation of the next generation imager, which will provide aerosol and fire radiative power measurements for the next generation of geostationary satellites. CSL should also consider how it's field campaigns could be designed to better understand the utility and value of the Tropospheric Emissions: Monitoring of Air Pollution (TEMPO) instrument dataset to NOAA and the national air quality interests. It will be difficult to utilize the TEMPO data confidently and appropriately until the uncertainty of the TEMPO data products has been adequately characterized.

Air Quality Recommendation #3: CSL modeling efforts should be expanded to include support for development of improved operational air quality predictions at national, global, and regional scales. In general, CSL air quality modeling efforts tend to focus on in-house (Weather Research and Forecasting model coupled with Chemistry, WRF-Chem) simulations, which are used to explore the impact of emissions and chemical mechanisms. CSL should consider widening their contribution to air quality modeling through additional strategic collaborations. CSL has a unique opportunity to improve the impact of their world class research through collaboration with GSL scientists at global (the Finite-Volume Cubed-Sphere Dynamical Cores, FV3, based United Forecast System, UFS) and regional (the stand-alone regional model, SAR FV3) scales. Similarly, CSL should consider a partnership with GSL to develop and operate a state-of-the-art high resolution contiguous U.S. (CONUS) air quality forecast that could contribute to a National Ensemble of Air Quality forecast models.

Air Quality Recommendation #4: Improve CSL's data management of air quality datasets by providing data in a timely manner and adopting open data policies. CSL lags other laboratories in terms of making data publicly available in a timely manner and setting up Digital Object Identifiers (DOIs) for datasets. For example, during the Stakeholder discussion, both the State of Colorado and California Air Resources Board representatives expressed some frustration that they experienced a long delay before getting access to the air quality data collected during CSL field campaigns. Another point of reference is that NASA is the process of adopting a new more inclusive Open Science paradigm, that includes data, information, and knowledge within the scientific community and the wider public (see https://www.essoar.org/pdfjs/10.1002/essoar.10505011.1 , and https://earthdata.nasa.gov/esds/open-science). A key component of Open Data policy is to have "open" science team meetings and data workshops where scientists who were not directly involved in the project can participate (via a virtual conferencing platform) discussions of the field campaign and learn more about how to potentially utilize this publicly available dataset in their own research.

Air Quality Recommendation #5: Continue to develop and support a collection of state-of-the-science instrumentation to allow for both rapid and repeated deployment. This allows for both scientific agility and fills a unique niche. This unique and integrated expertise needs continuous development and support, alongside with scientific mentoring. Approximately 70% of the CSL budget goes towards salaries and another 20% to overhead/rent, leaving a surprisingly small amount of funding for infrastructure and mission peculiar costs associated with field work (i.e., travel, instruments, software, hardware, etc.).

Air Quality Recommendation #6: CSL should continue collaborations with scientists at academic institutions and other agencies to continue to maximize impact and catalyze

research beyond NOAA. Communication could be improved to widen the suite of collaborators. While the collaborations have been extremely fruitful, there does not seem to be an overall strategy associated with building collaborations.

Air Quality Recommendation #7: Seek strategic collaborations to implement the air quality health effect link early in the research value chain. There are large disparities in the impact of air pollution. CSL performs some of the best air quality research in the world but has not demonstrated any meaningful interactions with air quality health effects experts in any projects other than TOAR. This is a great opportunity to ensure that CSL leadership is effective (e.g., as in TOAR) and to increase the value of CSL air quality research both nationally and internationally.

Air Quality Recommendation #8: Continue efforts to make efficient use of satellite products and prepare for full utilization through additional in-house expertise. CSL currently lacks sufficient expertise to adequately assimilate and fully integrate satellite observations of air quality/atmospheric composition (e.g., TROPOsheric Monitoring Instrument, TROPOMI, observations of carbon monoxide, CO, methane,CH_4, and nitrogen dioxide, NO_2; Cross-track Infrared Sounder, CrIS, observations of ammonia, NH_3, and isoprene; and Moderate Resolution Imaging Spectroradiometer, MODIS, Visible Infrared Imaging Radiometer Suite, VIIRS, and Geostationary Operational Environmental Satellite (GOES) observations of aerosol optical depth, AOD, and Fire Radiative Power, FRP) into CSL research. Now that it looks like the NOAA GEO-XO program is probably going to include a geostationary air quality instrument similar to TEMPO, it might be good for CSL to consider adding additional expertise in the assimilation and retrieval of column satellite trace gas observations (e.g., NO_2, ozone, O_3, formaldehyde, HCHO, SO_2, glyoxal, CHOCHO, etc.) from Ultraviolet/Visible (UV/VIS) spectrometers (e.g., Pandora, Geostationary Trace gas and Aerosol Optimization (GeoTASO), Geostationary Costal and Air Pollution Events, GEO-CAPE, Airborne Simulator, GCAS, TEMPO, TROPOMI, etc.).

3.2 Climate Research

3.2.1 Quality of Climate Research

The quality of the CSL climate research is outstanding for all three of the major climate research and development focus areas: Aerosol-Cloud Interactions (ACI), Aerosols and their role in Climate, and Greenhouse Gases (GHG) and Short-Lived Climate Forcers (SLCF). This high quality is demonstrated by the large number of climate related publications in high impact journals over the past five years. In addition, the panel also noted the multiple significant new climate related discoveries as well as the Laboratory's prominent international leadership and successful international collaborations related to climate research.

Finding: CSL's participation in the NASA EVS-2 ATom mission provided several important climate research discoveries. As part of the ATom mission, the dedicated and careful work of CSL scientists resulted in the first measurements of the global distribution of aerosol extinction in remote marine regions, measurements establishing the role of convective clouds in new particle formation in the upper tropical troposphere, and the discovery of a previously unobserved molecule, hydroperoxymethyl thioformate (HPMTF), which fundamentally alters our understanding of the oxidation products of dimethyl sulfide (DMS) and the marine sulfate budget and impact radiative forcing estimates of marine aerosols. In particular, the measurements of sea salt, black carbon, and dust aerosols by CSL scientists during ATom showed that climate models such as the NSF Community Earth System Model (CESM) overestimated sea salt, black carbon, and dust concentrations by orders of magnitude in the remote marine free troposphere. Then CSL scientists worked with CESM modelers to identify and improve model convective mixing parameterizations that lead to these discrepancies. These measurements, and the collaboration with NSF climate modelers to use the measurements to test climate model performance, resulted in improved simulations of the radiative impacts of natural aerosol and significantly reduced uncertainties in anthropogenic aerosol forcing. It is impressive to see how the exploitation of the ATom mission has already brought numerous insights and will continue to do so as the community has more time to analyze this rich dataset.

Finding: CSL's leadership in conducting ensemble Large Eddy Simulations (LES) of aerosol-cloud feedbacks, coupling these LES simulations to detailed Lagrangian cloud microphysics predictions is internationally recognized. CSL scientists use these complex aerosol-cloud models to interpret measurements from field campaigns such as the NOAA Atlantic Tradewind Ocean–Atmosphere Mesoscale Interaction Campaign (ATOMIC) mission to understand how aerosol concentrations modulate the formation of shallow marine clouds, which are key to understanding aerosol-cloud feedbacks within the climate system.

Finding: CSL's immense expertise in instrument development contributes to the high quality of CSL's climate research discoveries and is one of the highlights of the climate research theme. CSL scientists developed unique instrumentation such as the aircraft-deployable Laser Imaging Nephelometer, which provides in situ measurements of light scattering at fixed angles, to conduct the fundamental measurements needed to validate satellite aerosol optical depth retrievals. This validation is critical since the satellite measurements form the basis for assessing global aerosol distributions and trends. CSL's integration of laboratory studies, field campaigns, modeling, and instrument development is indeed unique. But the instrument development component is frequently overlooked by other laboratories. The review panel strongly encourages CSL to keep the instrument development budget funded at healthy levels to enable the Laboratory to continue to leverage this critical capability.

3.2.2 Relevance of Climate Research

Given that aerosols and clouds are the largest contributors to the uncertainty in climate projections, the CSL research has strong relevance to NOAA's mission and of high societal value to national and international priorities. CSL's climate research portfolio clearly addresses issues identified in NOAA strategic documents and research plans. Climate research efforts that are particularly relevant and display CSL leadership include: ATom contributions to understanding of the global aerosol budget, global-scale profiles of "AOD" from in-situ aerosol measurements, TOAR, and new CSL instrumentation to measure aerosol optical properties.

Finding: CSL's leadership of the Tropospheric Ozone Assessment Report (TOAR) has filled a significant gap in assessing the global distribution of surface ozone and trends. The TOAR-Climate work to characterize the global distribution of tropospheric ozone demonstrated that current satellite estimates of tropospheric ozone are not sufficient for monitoring global trends, which is an important finding and points to the need for more extensive measurements from the In service Aircraft for a Global Observing System (IAGOS) network. TOAR is a large gift to the scientific community as it enables us to "see" ozone distributions and trends worldwide that would not be easily perceived without the full TOAR dataset. TOAR has fed heavily into The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) Chapter 6 on Short-Lived Climate Forcers (SLCFs) and CSL leadership here was key. In the second phase of TOAR, the team plans to investigate the health implications of tropospheric ozone, and partnerships with other organizations will be critical to the success of this effort. Considering that the TOAR is highly relevant to human health ensures that it fits squarely into NOAA's vision and goals.

Finding: It will be important to continue to re-visit methane emissions from oil and gas production as there have historically been mismatches between top-down and bottom-up emissions estimates. The field campaigns to quantify emissions from natural gas formations are valuable to the nation and have highlighted the large uncertainty and high variability of this SLCF. It is worth noting here that quantifying speciated emissions from shale oil and gas operations is also of high importance to the air quality community and well deserving of future examination.

3.2.3 Performance of Climate Research

The CSL climate research performance is outstanding, and this is clearly reflected in the number of high quality publications and the excellent research leadership CSL provides in this area of critical national and international importance.

Finding: The laboratory management functions as a team and together works to improve the operation of CSL. As evidence of this, during the review, our discussions frequently came back to the CSL "Business Model" and culture that starts with a new idea/question/need which feeds into their integrated research approach which involves field campaigns, lab studies, instrument development, and modeling. CSL process level research is well integrated from end to end for climate (as well as the other two research foci). It is powerful because the model allows for a question to be iterated multiple times, following through the cycle generating results and new ideas each time until a process is more completely understood.

Finding: CSL should continue to pursue opportunities to be part of large multi-agency and/or multi-national field campaigns. Over the past five years, CSL was a reliable and trusted partner in several large national and international field campaigns. CSL's participation in ATom and FIREX-AQ, as both the instrument principal investigators (PIs) and leadership levels demonstrates the community's high level of regard for CSL's ability to develop, deploy, and deliver the high quality, comprehensive measurements that are needed to constrain aerosol direct and indirect radiative forcing. CSL's engagement of external climate modeling groups in the use of these measurements to test climate model simulations is commendable. Similarly, CSL's involvement in the Elucidating the role of Clouds-Circulation Coupling in Climate

(EUREC4A)/Atlantic Tradewind Ocean-Atmosphere Mesoscale Interaction Campaign (ATOMIC) was critical to the success of the project. ATOMIC was a key part of a larger multinational campaign that could not have been achieved by any one country.

Finding: CSL should continue to partner with other agencies to work on climate model development that is relevant to the IPCC. The Framework for Improvement by Vertical Enhancement (FIVE) within Energy Exascale Earth System Model (E3SM) is an interesting development and it is positive to see CSL scientists working with other agencies on model development. The CSL team should continue to look to see how the reductions in model biases relate to the model response to forcing. Similarly, CSL should further investigate how the radiative kernels work is being scaled up to the wider community and feeding into activities such as IPCC. There is a surge in interest in simple climate models (e.g., Reduced Complexity Model Intercomparison Project, RCMIP) and there could be good opportunities for the kernel work to be included in the report. Along the same lines, CSL should generate more examples like FIVE to show how the process-based modelling (e.g. large eddy simulation, LES) feeds into global climate models (GCM)/Earth System Model (ESM) development, since these are ultimately the tools used to make projections. e.g., parameterization development based on LES models.

3.2.4 Recommendations for Climate Research

Climate Recommendation #1: Consider repeating the systematic sampling of the remote atmosphere similar to the recent ATom field campaign. The insights gained from this field campaign were unpredictable and have been significant. The development (and new deployment) of new instrumentation could dictate the timing of such an effort. CSL leadership will be critical in developing and implementing an ATom 2.

Climate Recommendation #2: CSL climate science should also consider focusing on solutions and reducing risk. Climate research has historically been driven by scientific curiosity. However, future research should consider also focusing on solutions and reducing risk. This is especially important in an environment where politicians and the public are increasingly impatient and looking for quick approaches to directly modify Earth's radiation budget (ERB). CSL's new ERB research effort is an exciting and important opportunity for CSL research to provide careful, thoughtful, and unbiased scientific leadership to this critical climate issue. While the budget profile over the next five years may be uncertain, the panel wants to encourage CSL to continue to press for additional funding for ERB and recommends that CSL look for opportunities to collaborate with other Federal agency partners that do radiation budget research.

Climate Recommendation #3: Continue to use the CLS LES ensemble simulations to develop low-order, simplified models. The CSL climate team has an excellent opportunity to contribute he use of their LES models to create simple predator-prey and cellular network models that are currently under development to produce improved cloud-aerosol parameterizations for global climate models.

Climate Recommendation #4: Given the importance of the TOAR effort, CSL should consider adding a new scientist with expertise in the retrieval of tropospheric ozone from satellite sensors. This was a significant weakness in the first TOAR, and this challenge is going to be even more important as the community moves forward. While NASA and other parts of NOAA have this expertise, it might be best to have someone in house that is working directly with the TOAR leadership.

3.3 Stratosphere Research
3.3.1 Quality of Stratosphere Research

The CSL team is building on several decades of world class research and leadership in stratospheric research. CSL has long been known for its high-quality stratosphere-troposphere coupling research related to ozone, trace gas emissions, ozone layer depletion/recovery, and upper troposphere (UT)/lower stratosphere (LS) airborne observations. The review team was excited to learn more about the high quality CSL stratospheric research linked to surface weather prediction and the ERB initiative. There are many other powerful indicators of the CSL's high quality stratospheric research including the number of citations, the list of awards, the elected positions to prestigious organizations, service in technical and scientific societies and journals, and collaborations with other world class national and international research groups.

Finding: CSL stratospheric researchers have taken strong leadership roles and created meaningful scientific collaborations in significant international research initiatives. Some good examples of CSL's international stratospheric collaboration are the CSL scientists taking a strong leadership position in the Geoengineering Model Research Consortium (GMRC) and actively participating in the analysis of data generated by the Geoengineering Large Ensemble Project (GLENS). The panel also commends CSL scientists for their good connections into international scientific projects in particular Stratosphere-troposphere Processes and their Role in Climate (SPARC) through Stratospheric Network for the Assessment of Predictability (SNAP), Long-term Ozone Trends and Uncertainties in the Stratosphere (LOTUS), SPARC Reanalysis Intercomparison Project (S-RIP), and the Chemistry-Climate Model Initiative (CCMI).

Finding: CSL innovative new stratospheric in situ instruments are improving our understanding of stratospheric processes. CSL's new measurements of stratospheric aerosols using the POPS instrument that are critical for SAGE III validation and assessing the impacts of pyrocumulus black carbon and volcanic SO_2 on stratospheric chemistry. Similarly, the high-quality observations from the new CSLSO_2-LIF instrument with ~1 pptv detection limit was able to demonstrate that cross tropopause SO_2 transport is not a significant source of stratospheric aerosol mass. These in situ measurements have helped to resolve discrepancies in satellite retrievals of lower stratospheric SO_2 and provide more confidence in climate model predictions. Incidentally, the development and commercialization of the POPS instrument is a great example of lab innovation leading to a much wider impact on the atmospheric chemistry research field.

Finding: Development of the Stratospheric Water and OzOne Satellite Homogenized data set (SWOOSH) has been extremely valuable to the stratospheric ozone assessment community. CSL's leadership in the development of SWOOSH, which combines multiple satellite ozone and water vapor retrievals into a single climate data record, has been very beneficial to the stratospheric ozone assessment community. SWOOSH has been used in over 60 publications and continues to be updated.

Finding: The Tunable Optical Profiler for Aerosol and oZone (TOPAZ) lidar continues to make significant contributions to better quantify the contributions of stratospheric intrusions to surface ozone. CSL's TOPAZ team have made significant contributions to the communities understanding of the impact of stratosphere-troposphere exchange (STE) events on surface ozone enhancements in the western U.S. Several high-quality publications based on the TOPAZ measurements during the 2017 Fires, Asian, and Stratospheric Transport-Las Vegas Ozone Study (FAST-LVOS) provided detailed measurements of the impacts of STE and wildfire smoke on air quality.

Finding: CSL's high quality Sudden Stratospheric Warming Compendium (SSWC) is a good example of the Laboratory's creativity and ability to provide valuable data to the global community of scientists. The SSWC database provides an easy way to plot and download information on historical sudden stratospheric warming (SSW) events. This data set provides a strong basis for model evaluation and improvement. It has been used to explore the contribution of stratospheric vortex extremes to subseasonal to seasonal (S2S) predictability, which is a primary focus of the new NOAA UFS.

3.3.2 Relevance of Stratosphere Research

CSL stratospheric research and development efforts are highly relevant to NOAA's mission. The CSL stratospheric research portfolio directly addresses important and societally relevant needs both nationally and internationally. The CSL research team did a great job of highlighting how dynamical processes in the stratosphere affect humans and their day-to-day activities. In addition, the 2016/17 discovery of the surprise Trichlorofluoromethane (CFC-11) emissions increase in northeastern Asia was an incredible piece of careful detective work. This interesting story was embraced by the media and did a great job of highlighting the societal relevant research routinely performed by the CSL stratospheric team.

Finding: CSL stratospheric research is highly relevant to both U.S. and international interests. Recent foci have included very pertinent questions for the Montreal Protocol (CFC-11 emissions and compliance, ozone trends and recovery). The more recent work investigating the impacts of possible solar radiation management is relevant to governments considering this as a temporary mechanism to mitigate climate change impacts.

Finding: Over the years, CSL has continued to excel in taking laboratory studies all the way to their policy implications. The "stratosphere" research theme has evolved with time, moving from polar ozone depletion issues in the 1980-present to now more of an aerosol and black carbon focus. CSL has demonstrated amazing strengths in taking laboratory experience, equipment, and knowledge to targeted field campaigns that result in high impact science publications. These publications do a good job of exploring and explaining the important policy implications.

3.3.3 Performance of Stratosphere Research

CSL is highly effective in planning and conducting its stratospheric research and development given the resources provided. The CSL stratospheric scientists have continued to maintain their outstanding research which improves our understanding of stratospheric composition and dynamics as well as the adherence to the Montreal Protocol.

Finding: CSL's stratospheric aerosol research is well poised to make a significant impact on our understanding of the stratosphere. The CSL POPS balloon sonde measurements are a critical component of the stratospheric observing system. Similarly, the review panel is looking forward to seeing the fruits of CSL's strong research efforts related to short-wave stratospheric aerosol radiative forcings and the impacts of stratospheric aerosols on ozone as part of the new ERB initiative.

3.3.4 Recommendations for Stratospheric Research

Many of the highest profile pieces of work in the stratosphere research theme have been what could be categorized as 'responsive', i.e., rapid studies that address a specific unusual observed event (e.g., CFC-11 evolution, lower stratospheric ozone evolution, 2015-16 stratospheric water, wildfire smoke in stratosphere etc.). CSL is highly adept at 'following their nose' to probe such case studies which frequently lead to papers in high profile journals. The panel would like to challenge CSL to more clearly integrate the 'responsive mode' with the longer-term view of identifying what are the major outstanding questions in stratospheric science and the CSL strategy for how these questions will be addressed. The panel would have benefited from seeing more about how the pieces fit together from a strategic perspective as well as being driven by the interests of individual scientists.

Stratosphere Recommendation #1: Moving forward CSL should continue to focus on the impact of replacements for CFCs and observational strategies to continue ensuring a consistent long-term record of the evolution of stratospheric composition.

Stratosphere Recommendation #2: CSL should continue to expand the budget for POPS Balloon Baseline Stratospheric Aerosol Profiles (B2SAP) project, particularly with the new focus on climate intervention studies.

Stratospheric Recommendation #3: CSL should leverage the potentially short-term ERB funding to support activities that will build strengths and skills in CSL that can be continued beyond the ERB lifetime.

Stratospheric Recommendation #4: The CSL chemistry-climate group, which has recently lost two modelers, should be a high priority for both the long-term retention of current modelling expertise and the potential location for a new hire.

3.4 Research Strategy

CSL's integrated research approach, with a continuous cycling of instrument development, laboratory studies, field campaigns, and modeling is highly effective and adaptable. This research strategy has been the cornerstone of CSL's research for decades and has demonstrated success through effectively using results from each stage of the research cycle and building upon it to advance the science at a national and international level.

Finding: CSL's holistic approach to understanding the Earth system is central to its success. The CSL research strategy is designed to meet NOAA OAR's goals to detect changes in the atmosphere, make better forecasts, and drive innovative science. At the heart of this strategy is an integrated research approach that equally relies on laboratory studies, field campaigns, modeling, and instrument development. Over the years, this fundamental research strategy has been very successful at addressing their core science goals while also resulting in a surprising number of significant and unanticipated discoveries. This high performance is evidenced by many indicators, including high profile/impact scientific publications, new measurement technologies, awards and citations for laboratory staff, elected positions in prestigious scientific organizations, etc.

Finding: The CSL research strategy has been better at promoting instrument development than model development. Over the years, the CSL research paradigm has developed world-class instruments (21 new and custom instruments since 2015!), lab studies, and field campaigns. Across all these areas there is a wealth of expertise and excellence. Based on the presentations and discussions during the 2021 CSL Science Review, the panel's impression was the CSL modeling expertise is narrower in specific areas (e.g. LES) and that the bulk of the CSL modeling research is as model users rather than developers. There is a great opportunity for CSL to both collaborate with model developers and to hire new staff with this expertise. The benefit of building more strength in model development could result in a better connection between CSL research and NOAA operations/applications.

Finding: The CSL high sensitivity and fast response nitric oxide laser-induced fluorescence (NO-LIF) instrument is a potential game changer. Another notable research highlight is the development of high sensitivity measurements of NO, potentially opening the door to explore in depth the chemistry in remote/low NOx environments. If this new CSL NO instrument could be combined with one of the new/next generation of LIF NO_2 instruments (under development at MPI/FZJ and NASA and NCAR), then we can look forward to precise measurements of nitrogen oxide (NOx) budgets and NOx eddy covariance. Such instruments are potential game changers!

Finding: CSL research is guided by NOAA OAR research priorities. It is clear to the review panel that CSL leadership and staff make research decisions that are guided by the stated NOAA OAR research priorities. Consequently, CSL research makes significant contributions to the Nation's societally relevant needs. The review panel's discussions with the CSL stakeholders also confirmed that the Laboratory has meaningful and well-developed relationships that are meeting the stakeholders' needs.

Finding: CSL's research strongly supports the Montreal Protocol. CSL's laboratory evaluation of ozone depleting substances (ODSs) and potential replacement compounds provides critical scientific data needed to satisfy the Montreal Protocol and amendments that quantify ozone depletion potential (ODP) and global warming potential (GWP) on hydrochlorofluorocarbons (HCFCs).

Finding: CSL's research directly supports NOAA's development of the Next Generation Global Prediction System (NGGPS). CSL's focus on process level modeling of PBL dynamics, development of reduced chemical mechanisms, and use of ATom field campaign data to evaluate the fidelity of the UFS aerosol predictions directly supports NOAA's development of NGGPS and improved forecasting of smoke emissions and transport within the operational HRRR-Smoke forecast.

Finding: CSL conducts its research in a highly efficient manner. As a result of CSL's holistic and integrated research strategy, when the Laboratory takes on a new project, they are careful to clearly define and document their scientific objectives, rationale, and methodologies. A particular project's research strategy is always described in a publicly available "white paper" that can be found on a dedicated public website. Another metric or indicator of the high performance of the CSL research strategy is the efficient way the laboratory conducts its research and development. The review panel was surprised to learn that the CSL laboratory's annual internal OAR budget (~ $15 M) was not a bit larger. It is helpful that CSL is successful in obtaining funds from other agencies. The panel was also surprised to see such a small fraction of CSL's overall funding (9%) was available each year for "other" things, which include: purchasing instruments or paying for Mission Peculiar Costs. Given that ~71% of the budget is for salaries and ~19% is for Overhead and Rent, there is not much room left for travel and equipment. So, it is great to see how efficient and successful the Laboratory has been with their limited resources for discretionary spending, other mission costs, and investments in the new technologies.

Finding: CSL's instrument development and laboratory expertise is world class and truly a national asset. A quintessential example of this was CSL's ability to identify the role of volatile chemical products (VCPs) in urban VOC emissions, conduct laboratory studies to establish the needed relevant rate constants, and then develop the reduced chemical mechanisms for representing these in a model.

3.4.1 Recommendations for Research Strategy

Research Strategy Recommendation #1: CSL should ensure stable base funding of it's instrument engineering staff and plan ahead by developing viable succession plans for each staff member, because this team is critical to the continued success of CSL's integrated research strategy.

Research Strategy Recommendation #2.: CSL should aspire to make their research enterprise more open by adopting Open Data and Open Source Software policies. CSL should make sure to implement data workflows that make CSL (field)-data readily findable and assure getting acknowledged by creating DOIs for all their datasets. CSL might take a closer look at the new NASA Open Science initiative, which defines open science as a collaborative culture enabled by technology that empowers the open sharing of data, information, and knowledge within the scientific community and the wider public to accelerate scientific research and understanding (see https://www.essoar.org/pdfjs/10.1002/essoar.10505011.1, and https://earthdata.nasa.gov/collaborate/open-data-services-and-software). The Open Science initiative would encourage CSL to open up their science team meetings and data workshops to the greater community of atmospheric scientists. This effort also includes an Open Source software policy as well as the use of community-driven tools such as the Common Metadata Repository (CMR).

Research Strategy Recommendation #3: CSL should purposefully reach out to better incorporate Historically Black Colleges and Universities (HBCUs) into their research and development enterprise. The atmospheric chemistry field has done a poor job of developing and recruiting African Americans (and other marginalized peoples) into our laboratories. However, NOAA has a unique and substantial long-term investment in the NOAA Cooperative Science Center in Atmospheric Sciences and Meteorology (NCAS-M) that is led by Howard University. CSL could reach out to Howard University and the NCAS-M students and faculty and incorporate them into their laboratory studies and field campaigns. CSL frequently works with CU-Boulder engineering students to help with their instrument development (e.g., the micro-pulse Doppler lidar and the miniature Airborne Cavity Enhanced Spectrometer). Certainly, the fact that CU-Boulder is less than a mile down the road from CSL makes this much easier, however, in the future CSL could try to enlist the help of engineering students in the Howard University College of Engineering. To build the pipeline, CSL should also consider implementing a summer internship program for underrepresented or marginalized undergraduate students that brings the students to the CSL laboratory for a couple of months and gets them involved in and excited about the CSL R&D environment.

Research Strategy Recommendation #4: CSL should complement their laboratory studies with theoretical chemistry expertise through strategic collaborations and partnerships.

Research Strategy Recommendation #5: CSL should reinvest in and reestablish their heterogeneous chemistry expertise. CSL's new focus on ERB will require additional expertise in heterogeneous chemistry so that the impacts of potential climate mitigation strategies on stratospheric ozone chemistry can be assessed.

Research Strategy Recommendation #6: CSL should continue to invest in the development of machine learning. In particular, machine learning techniques or artificial intelligence (AI) approaches will be useful for data analysis, chemical mechanism, and data assimilation that might be too numerically expensive otherwise. The use of machine learning (e.g., application of pattern recognition techniques) could facilitate a greater usage of satellite data and allow models to operate at finer spatial scales.

3.5 Leadership

The CSL leadership team has done an outstanding job of providing the CSL staff/team with clear guidance related to the scientific objectives, rationale, and methodologies. The Laboratory leadership team has developed and nurtured a culture that consistently and continually evaluates projects in a fair and transparent manner, which results in a cohesive and effective CSL team. Based on the results over the past five years, it is clear that the CSL leadership team is committed to ensuring that the CSL research and development enterprise shows strong linkages to NOAA’s Research mission and priorities, and is of value to the Nation. It is particularly noticeable that most, if not all, of the CSL research efforts clearly address societally relevant needs, both nationally and internationally.

Finding: CSL leadership is crucial to the success of several major national and international policy relevant research initiatives. CSL has prominent leadership of the WMO Ozone Assessment Reports, the NCA4 and TOAR. The WMO Ozone Assessments and NCA4 have direct routes into policy making and are vital channels to feed the latest science through to governments. They relate to the major environmental and societal threats from ozone depletion and climate change. TOAR is more oriented at the scientific community but with an awareness of wider stakeholders (e.g. IPCC). CSL leadership is crucial to the success of these major initiatives.CSL work in these organizations is of the highest quality and its scientists are recognized leaders.

Finding: CSL's leadership fosters a culture of creative PI-led independent research that fosters scientific advancement. Critical to this is the role of internal seed funding which provides opportunities for CSL PIs to develop new concepts, instrumentation, and measurements that feed the CSL research strategy.

Finding: CSL leadership assures that the Laboratory goals are closely aligned with NOAA research objectives. CSL leadership worked hard to establish a close collaboration with other OAR labs, in particular the Global Monitoring and Global Systems Laboratories (GML & GSL). CSL leadership might explore the opportunity to work more closely with ARL to influence and improve the National Air Quality Forecast.

Finding: CSL's leadership and contributions to issues of interest to NOAA and the Nation. The work done in leading the national assessment reports and the leadership shown to assess the impact and and scientific merit of the recent Earth's Radiation Budget proposals are good examples of CSL's large leadership impact on issues of national importance. Other examples include the SWOOSH database and the use of lidar in wind-energy and numerical weather prediction are others are examples of CSL leading our community. Also noteworthy is how CSL leadership makes it a priority to clearly assess and translate scientific understanding for stakeholders and policymakers.

Finding: The demographics of the CSL leadership is grossly imbalanced with respect to gender and racial composition. The lack of women and others from marginalized communities in CSL leadership positions is noticeable. The review team realizes that it takes time to recruit and develop leadership within the organization; the lack of diversity in the new/recent hires also makes this particularly challenging. A couple of CSL's peers (i.e., other national laboratories dedicated to atmospheric science/composition) seem to be doing a bit better at including diversity within their leadership.

Finding: CSL's leadership is effective at reaching out to early career staff to discuss research progress on a personal basis. The CSL Science Review effectively highlighted the work of early career scientists.

Finding: CSL scientists should take a more prominent role in the IPCC. For example, the review panel is not aware of any CSL scientists that are Lead Authors in IPCC AR6.

Finding: CSL's role in the creation and leadership of TOAR is commendable. This important initiative was started from CSL and led by a CSL scientist. The first assessment produced the world's largest database on tropospheric ozone and created a special feature of highly cited publications in, *Elementa: Science of the Anthropocene*. The TOAR database is entirely open-access, allowing anyone to download the ozone metrics and conduct their own research. The Quality Assurance/Quality Control (QA/QC) processes developed for TOAR were reported back to international air quality agencies and research data repositories and used by scientists around the world to access quality data. In many cases, these reports have led to improvements in the primary data archives. The leadership of CSL in TOAR has also resulted in close involvement in the IPCC AR6 chapter 6 on SLCF. Data and metrics from TOAR were also recently included in the Global Burden of Disease Study 2019 published in *The Lancet*.

3.5.1 Recommendations for Leadership

Leadership Recommendation #1: More effective communication between CIRES and CSL leadership regarding career advancement opportunities. Early career CIRES scientists play a key role in many of the research teams at CSL. However, these staff members expressed some uncertainty regarding how to advance their career at CSL. The panel also recommends conveying these opportunities to the early career scientists at annual performance reviews.

Leadership Recommendation #2: CSL leadership should work hard to create a strong culture of diversity and inclusion throughout the organization. CSL leadership should make a concerted effort to enhance the diversity of both the laboratory and the leadership team. The CSL leadership needs to clearly communicate your diversity strategy. The NOAA website states that the agency "is firmly committed to increasing the Diversity within its workforce and creating Inclusive work environments where everyone feels valued and experiences a true sense of belonging. At the same time, NOAA openly acknowledges that a lot of work is needed to get where we want to be in terms of diversity and inclusion. NOAA will continue to take direct steps to increase the diversity of its workforce as well provide an inclusive work environment for all employees." The NOAA Inclusion and Civil Rights website goes on to say: "NOAA's ultimate goal is to not only embrace these concepts, but ensure they are fully integrated into the agency's business practices and more importantly its organizational culture. To accomplish this goal, NOAA's Office and Inclusion and Civil Rights has developed a series of multi-year Diversity and Inclusion Strategic Plans to steer the agency in the right direction and keep it on course."

Leadership Recommendation #3: Ensure support for CSL scientists to take on leadership roles within future IPCC assessments.

Leadership Recommendation #4: Continue to support and promote CSL scientists as leaders of activities within the World Climate Research Programme (WCRP).

Leadership Recommendation #5: CSL needs to continue its leadership and important role in the national discussion on research of climate interventions.

4. Summary Recommendations

CSL should be commended for their body of work as well as their professional and efficient presentation of scientific output over the review period. They are truly performing at the highest level and set the bar for other organizations in the international community. While it was not practical to give specific mention to everything that was presented, the breadth and quality of research taking place at CSL is impressive.

It was a pleasure for the reviewers to have the opportunity to virtually interact with OAR and CSL management and staff. The frank and open discussions with scientists as well as stakeholders were constructive in helping the panel to develop recommendations intended to strengthen an organization that is already highly influential. These recommendations have already been discussed in more detail above, but are all listed below in one location for convenience.

Panel Summary Recommendation #1: CSL needs to improve the diversity of its leadership and staff.

Panel Summary Recommendation #2: The CSL Research Strategy which encourages a high level of integration between field campaigns, laboratory studies, modeling, and instrument development across all research foci leads to outstanding research and should be actively nurtured and maintained.

Panel Summary Recommendation #3: NOAA OAR should continue to entrust CSL leadership with the management of the Laboratory's research funds and scientific direction.

Air Quality Recommendation #1: CSL research could better integrate environmental justice in considering how to prioritize scientific topics.

Air Quality Recommendation #2: CSL scientists should continue to play an active role in defining the components and preparing for NOAA's Geostationary and Extended Orbits (GEO-XO) satellite system.

Air Quality Recommendation #3: CSL modeling efforts should be expanded to include support for development of improved operational air quality predictions at national, global, and regional scales.

Air Quality Recommendation #4: Improve CSL's data management of air quality datasets by providing data in a timely manner and adopting open data policies.

Climate Recommendation #1: Consider repeating the systematic sampling of the remote atmosphere similar to the recent ATom field campaign.

Climate Recommendation #2: CSL climate science should also consider focusing on solutions and reducing risk.

Climate Recommendation #3: Continue to use the CLS LES ensemble simulations to develop low-order, simplified models.

Climate Recommendation #4: Given the importance of the TOAR effort, CSL should consider adding a new scientist with expertise in the retrieval of tropospheric ozone from satellite sensors.

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Stratospheric Recommendation #4: The CSL chemistry-climate group, which has recently lost two modellers, should be a high priority for both the long-term retention of current modelling expertise and the potential location for a new hire.