Summary Report of the Review of the NOAA Air Resources Laboratory

March 22-24, 2022
Virtual

Review Panel

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Introduction

A review of the Air Resources Laboratory (ARL) was conducted March 22-24, 2022 in a virtual mode. The purpose of the review is to evaluate the quality, relevance, and performance of research conducted by NOAA ARL. Such reviews ensure that ARL's research is linked to strategic plans, and priorities; is of high quality; and is conducted efficiently and effectively. This summary report is a compilation and synthesis of individual panel member comments. No attempt has been made to develop a consensus position on any specific topic. The report is organized according to the three research themes: surface-atmosphere exchange, atmospheric transport and dispersion, and boundary layer characterization. Within each section, a brief summary is followed by general comments and a set of actionable recommendations. A full list of abridged recommendations is included as an appendix.

The review team thanks NOAA staff for the development of very high-quality presentations and other review materials. Instructions to panel members were clearly communicated and NOAA administrative, management, and scientific staff were accessible and responsive throughout the entire review process. Follow-up questions were quickly addressed. Overall, the review was very well planned, managed, and executed. While in-person meetings are optimal, this virtual review was successful due to the extensive preparation by NOAA staff. The panel recognizes and appreciates this effort.

Over-arching Comments and Recommendations

Comments

ARL's activities are well aligned with NOAA and OAR goals.

ARL continues to demonstrate its commitment to scientific excellence. The contributions of the laboratory and its staff to the atmospheric transport and dispersion community are widely recognized and are often deemed invaluable and irreplaceable by stakeholders in all sectors. The dedicated and tireless efforts of the ARL team have been critical to the organization's success.

The laboratory develops, maintains, and operates state-of-the-science tools and capabilities that are also *critical* to a wide range of applications and missions *outside* of DOC (e.g., academia, private sector, DOE, and DOD).

ARL and its scientific staff continue to be recognized by the community as leaders in their fields. This was quite evident in the generally positive stakeholder feedback.

ARL has been responsive to the 2016 review.

The continuity and productivity across programs during the COVID-19 pandemic despite evident challenges is impressive.

Stakeholders noted that ARL staff are very collaborative and responsive.

Multiple bibliometric indicators show very high value and impact of research. Annual publication targets are consistently met or exceeded. Given the size of ARL and focus of the group on also transferring research to operations, keeping such a publication record is commendable. It is noted that several researchers occupy national and international leadership positions. Scientific work and researchers have received numerous prestigious awards/recognitions.

HYSPLIT continues to be widely used by the community and it is recognized as an irreplaceable capability not available anywhere else for research and operations.

The ARL team has successfully bridged research to operations and operations to research with HYSPLIT. They actively seek opportunities to augment their operational model by integrating new capabilities (e.g., TCM, STILT). They also take feedback from their userbase to streamline the code and to inform/guide future model developments.

ARL's research expertise in atmospheric dispersion, boundary layer characterization, emission data inversion, and MesoNets could serve as the basis for an integrated approach to better characterize the urban atmosphere and inform environmental justice issues. ARL is well positioned in this regard.

ARL has many high-quality, high-recognition products (e.g., HYSPLIT, USCRN), but there is a need to increase the general visibility of ARL's staff and activities beyond niche communities (i.e., enhance ARL's "brand recognition").

ARL ATD operates efficiently with a highly effective work force. Funding levels and sources have remained mostly static the past three years with about 2/3 of the funds from "base" sources (which fund federal salaries, some CI salaries, and the CRN) and about 1/3 of the funds from reimbursable accounts. Having multiple funding sources such as this requires leadership to navigate many relationships and demands.

ARL leadership demonstrates visionary thinking and flexibility in responding to emerging needs, capabilities, and unanticipated events. Leadership serves as a model for other organizations.

Having staff from 3 separate Cooperative Institutes, managed at the Division level vs the Director's office, seems less than optimal. Furthermore, the use of three distinct CIs with three different sets of operating practices risks creating tensions. Different approaches to recruitment, retention, promotion, training, etc. risk the creation of an effective caste system depending upon which CI staff belong to. Careful monitoring is required to guard against this.

Leadership is excellent in fostering a safe, collaborative, and productive environment for Lab staff while navigating budget challenges and reorganizations. This was especially evident from talking with the CI's and post-docs. They are collegial and encouraging with each other and appreciate the work their leadership does protecting them from bureaucratic issues and enhancing their working environment. They are encouraged to pursue their interests and to take training, for example having the opportunity to take courses at the University of Maryland. Based on CI/postdoc feedback, ARL leadership appears to foster a positive and inclusive workplace culture.

In terms of staff development, the commitment of the organization to encourage staff to seek out opportunities for development is commendable. To quote one of the personnel interviewed "We don't expect a 'no' if we ask to go to a workshop, training, etc". The fact that staff feels this way with such conviction signals a healthy environment in which advancing knowledge is a top priority.

ARL leadership has done a phenomenal job navigating leadership transitions and minimizing impacts to its scientific and technical staff.

The HYSPLIT team has done a wonderful job developing and supporting the system while maintaining backwards compatibility and version control. The scientific staff supporting the development and operation of the HYSPLIT model is small. As the number of HYSPLIT users and applications continues to rapidly increase, it will become imperative to inject additional resources into the support of this critical capability.

Recommendations for the Laboratory

1.1 ARL should supplement its strategic plan with prioritized thrust areas that consolidate complimentary research objectives across the Surface-Atmosphere Exchange, Atmospheric Transport and Dispersion, and Boundary Layer Characterization program areas.

1.2 Though the diversity of projects that ARL staff contribute to is impressive, in some instances the level of involvement was not apparent. While this may be a consequence of changing stakeholder needs, in the long-term some balance between fulfilling short-term stakeholder needs and building an anticipatory research program that cultivates the lab's core capabilities may be desirable. Where possible, OAR and ARL management should seek opportunities that also help with the formulation of anticipatory research.

1.3 ARL should prioritize the modernization of the HYSPLIT code and web-based functionalities to ensure portability and adequate (or enhanced) performance in emerging computational platforms (e.g., HPC, cloud, GPUs). To enable these efforts, ARL is encouraged to continue to identify and inject its infrastructure needs into OAR strategic planning.

1.4 ARL needs to update its websites and improve data repositories to make them more accessible (e.g., improved APIs, discoverability, and metadata). This was a common suggestion for improvement among stakeholders.

1.5 There is concern about program continuity, as it seems some ARL programs are led by a single federal staff member (with several nearing retirement age). ARL should actively work to build redundancy of expertise in scientific and technical areas that could be affected by retirements in the near term. The development of a strategic plan to address gaps resulting from lack of redundancy due to talent attrition (e.g., retirements, promotions, lateral moves) should be pursued.

1.6 The extended use of "acting" roles within the ARL ranks, especially leadership roles, is troubling. OAR should prioritize completing all hiring actions for ARL leadership staff.

1.7 The precarity of non-federal positions and declining federal workforce present medium to long-term risks. While there is a role for contractors and cooperative institutes, they should be value-added and not critical to core mission aspects. As such, efforts should be undertaken to convert posts where possible to federal positions.

1.8 International engagement is principally in the form of committees and working groups with little evidence for sustained collaboration with international partners, particularly outside North America. This risks under-exploitation of the useful tools and approaches developed by the lab. An international engagement strategy would be valuable. Long-term win-win partnerships should be sought which may increase support either directly or through in-kind collaborations. Examples exist such as the collaboration between NOAA NCEI and C3S on collection and management of global in-situ data holdings.

1.9 Principal reported conference engagements were at AGU and AMS. While these are undoubtedly valuable and have high visibility, more specialized conferences and workshops on focused topics (e.g., fire) are oftentimes more valuable in terms of networking and gaining insights and engagement. A more balanced portfolio of meetings attended may yield dividends and better community engagement. Consideration should also be given to attendance at relevant international meetings to broaden impact.

1.10 ARL is to be commended for its mentoring and outreach efforts. However, ARL should continue to develop and provide leadership opportunities to its female scientific staff.

1.11 ARL should actively engage users in DOD, DOE, and other US government organizations to identify opportunities for collaboration, including classified applications. To facilitate these efforts, a greater number of staff members with clearances might be needed.

1.12 ARL should invest into growing support staff for the HYSPLIT model to better balance research and development efforts with ever-growing operational support requirements, including code dissemination and management, user training, and real-time support (e.g., READY).

1.13 ARL's plans for the advancement of atmospheric transport and dispersion applications appear well aligned with user community needs and requirements. The organization is encouraged to pursue these very critical topics fully.

1.14 ARL should explore opportunities to align its current efforts in urban air quality research to more directly address environmental justice issues. ARL seems very well positioned in this regard.

Theme	Rating	Reviewer						
		John Walker	**Rohit Mathur**	**Dave Turner**	**Erik Kabela**	**Susan O'Neill**	**Astrid Suarez-Mullins**	**Peter Thorne**
Overall ARL	Overall	Exceeds Expectations	Exceeds Expectations	Exceeds Expectations	Exceeds Expectations	Highest Performance	Exceeds Expectations	Exceeds Expectations
Surface - Atmosphere Exchange	Overall	Highest Performance	Exceeds Expectations	Exceeds Expectations				Exceeds Expectations
	Quality	Highest Performance	Highest Performance	Exceeds Expectations				Exceeds Expectations
	Relevance	Highest Performance	Highest Performance	Highest Performance				Highest Performance
	Performance	Exceeds Expectations	Exceeds Expectations	Exceeds Expectations				Exceeds Expectations
Atmosphere Transport and Dispersion	Overall	Highest Performance	Highest Performance	Highest Performance	Exceeds Expectations	Highest Performance	Highest Performance	Exceeds Expectations
	Quality	Highest Performance	Highest Performance	Highest Performance	Exceeds Expectations	Highest Performance	Highest Performance	Exceeds Expectations
	Relevance	Highest Performance	Highest Performance	Highest Performance	Exceeds Expectations	Highest Performance	Exceeds Expectations	Exceeds Expectations
	Performance	Highest Performance	Highest Performance	Highest Performance	Highest Performance	Highest Performance	Highest Performance	Exceeds Expectations
Boundary Layer Characterization	Overall	Exceeds Expectations		Exceeds Expectations	Exceeds Expectations			Exceeds Expectations
	Quality	Exceeds Expectations		Exceeds Expectations	Exceeds Expectations			Exceeds Expectations
	Relevance	Exceeds Expectations		Exceeds Expectations	Highest Performance			Highest Performance
	Performance	Exceeds Expectations		Exceeds Expectations	Exceeds Expectations			Exceeds Expectations

Research Area: Surface-Atmosphere Exchange (Lead Reviewers: Rohit Mathur, John Walker)

Brief Summary

ARL's research in this theme aims at improving the understanding of surface-atmosphere exchange of momentum, energy, and mass (moisture, trace constituents-gases and aerosols) to better characterize the dynamics and composition of the atmosphere and improve process representations in weather and climate models. Research in this area contributes to programs of national significance including the development and scientific evolution of the National Air Quality Forecast Capability and observations under the Surface Energy Budget Network. ARL's work on long-term mercury measurements contributes to better understanding trends in atmospheric mercury levels and assessing impacts of control measures. The evolving work related to aircraft-based air pollutant measurements has potential to inform local and national emission inventories. Overall, the worked performed by ARL under the surface-atmospheric exchange theme (i.e., surface energy balance, aerosol flux, and surface exchanges) is relevant to and aligned with OAR strategic goals, specifically to develop interdisciplinary Earth system models and to transition science that meets users' current and future needs.

Quality

The work performed by the surface-atmosphere exchange group (SAE) is clearly of very high quality as indicated by citations and use of data.

The SAE group generates novel datasets that serve stakeholders in other Agencies and the broader scientific community.

The diversity of ARL's research portfolio in the area of surface-atmosphere exchange is impressive and spans observations from multiple platforms, a broad spectrum of chemical constituents, development of parameterizations and algorithms for inclusion in atmospheric models, and adaptation and transfer of models and data to operations in support of air quality forecasting.

ARL has and continues to play an important role in supporting NOAA's national level air quality forecasting system and their efforts in improving the science of select components (e.g., wind-blown dust emissions), coupling the chemistry-transport model to the evolving weather forecast system and developing data sets to support operations (representative emissions) have helped improve forecast skill.

In work with the NWS, ARL could not only help with the transition of models and datasets to operations for the NAQFC but could also identify and evolve research that addresses issues related to seasonal and sub-seasonal forecasting of atmospheric composition. ARL's work on air-surface exchange may naturally lend itself to this area.

The continuation of measurements to support multi-decadal records of surface-energy budget for different land surface types is also an important activity to support climate assessments and evaluation of models.

ARL operates tools and capabilities that are critical to a wide range of applications.

The mercury monitoring program is world-class and seen as highly important by the stakeholder community.

High quality observations of unique global value in some cases. Modelling applications are of sustained high quality.

NAQFC is an excellent product.

ARL work on reactive chemical fluxes is cutting edge and highly important to improvement of surface-atmosphere exchange algorithms in chemical transport models.

Novel aircraft-based measurements of greenhouse gas concentration and fluxes are advancing current understanding of urban greenhouse gas budgets and flux processes in heterogeneous natural landscapes.

Relevance

The work performed by the Surface-Atmosphere Exchange group is very relevant to NOAA's mission and is well aligned to many of the Agency's strategic goals. The work supports the scientific evolution of the national air quality forecast system and contributes to national observational programs (AMNet, SEBN). Much of the work in this area builds on historical strengths of the lab which are unique within the Agency.

ARL research in this area is relevant to the needs of a broad stakeholder base from model development and evaluation, climate assessments, air quality and ecosystem exposure assessments, and improvement of emission inventories.

Research on surface-atmosphere exchange of reactive nitrogen and aerosols, both measurements and modeling, is highly relevant and complementary to broader efforts within other Agencies and the scientific community.

The rationale for focus on certain chemical constituents was not always apparent. While the quality of the work was excellent and research yielded important scientific insights, establishing linkage to an overall cohesive laboratory vision would help better convey the relevance of these efforts.

Many applications and missions are for agencies outside DOC (primarily DOE, but also private sector, academia, and DOD).

Findings as published are of clear national and international relevance.

Performance

The diversity in the work performed and the number of products delivered is impressive. It is clear that given the relatively modest size of the different project teams, the members of the Surface-Atmosphere Exchange group are high performers.

Perhaps due to the nature of the work involved with supporting operations (either for operational systems at NWS or measurement sites within networks), the team often appears to be involved with multiple and sometimes duplicative efforts (e.g., implementing and supporting similar schemes or data in multiple modeling systems: GOCART, RRFS-CMAQ, GEFS-Aerosol). The alignment of these efforts will hopefully improve as there is convergence on the design and components of the Unified Forecast System, but in the interim some coordination appears to be needed to minimize duplication and ensure that efforts and personnel are not spread out too thinly.

There is some concern about the continuity of programs currently lead by a small number of key personnel, in some cases a single PI.

Recommendations for this Research Area

2.1 Development and testing of the air quality components in the UFS framework should be continued as they often help identify issues related to transport and conservation that may not be diagnosed through NWP applications alone. It appears that some representation of the large-scale forcing beyond the current GEFS-GOCART system may be needed to capture changes in global emissions and their impacts on long-range pollution transport to North America. Development of a low resolution UFS-CMAQ system for creating space and time varying chemical lateral boundary conditions or use of other systems (e.g., Copernicus) could be explored.

2.2 Migration of the NACC code to the AWS platform to expand userbase for the FV3GFS-CMAQ for other regional domains across the globe is a worthwhile activity and should be continued.

2.3 ARL invests significant effort in creating emission data sets to drive the NAQFC system and in the future may be pursuing similar efforts on the global scale for the UFS. Documenting the changes in these data sets (for instance relative to the NEI for the U.S.) and making them publicly available may help increase their utility and promote transparency in the overall forecast products.

2.4 In many instances it seems that opportunities exist to broaden the utility and impact of ARL's research and development activities:

(i) Several examples were presented where ARL research led to development of new emission data sets for select species (e.g., CH_4 for Maryland, Volcanic SO_2) or sectors (wildfires in the future). These data have broad potential use and should be made publicly available for use by the broader scientific community, which would help promote ARL and NOAA's research efforts.

(ii) The initiation of collaboration between ARL and GFDL to apply the SEBN data for evaluation and improvement of land-surface models is a positive development. Similar collaborative efforts where ARL measurements can help inform development of scale-aware processes in earth system models should be actively pursued and encouraged.

(iii) Long-term Hg measurements provide unique opportunities to assess and contrast trends in Hg speciation and possible shifts in seasonal behavior across different locations (background, suburban, Arctic) and serve as useful tests for models. Continued analysis of this nature and collaboration with modeling groups should be pursued.

2.5 New collaborations (e.g., with DOE's Atmospheric System Research program) would provide additional opportunities and datasets to improve air quality model (NAQFC) and should be encouraged.

2.6 Consider viability of expansion of the SEBN network to have a permanent presence in Alaska to monitor the rapidly changing Arctic climate, preferably paired with a USCRN site.

2.7 A contingency plan is required for if UFS leads to unacceptable degradation of model-based applications. Is there a formal lock on UFS release depending upon implications for the composition models? If not, is there a fall-back plan for continuity of existing products unless and until acceptable (comparable or better) performance than existing systems can be found?

2.8 Setting up a research version of a low resolution global UFS-CMAQ system for creating space and time varying chemical lateral boundary conditions for regional NAQFC could help explore possible impacts of changing large-scale forcing and global emissions on daily air quality forecasts and provide guidance for evolution of the operational system.

2.9 ARL efforts to apply multi-layer models to better understand in-canopy processes influencing net canopy-scale fluxes of reactive gases and aerosols is unique relative to other agencies and academia and should be continued.

2.10 Development and application of large eddy simulation as a tool to better understand surface-atmosphere exchange processes is encouraged, particularly for deep canopies and complex environments.

2.11 Direct measurements of surface-atmosphere exchange of ammonia and relevant biogeochemistry/surface conditions in natural and agricultural landscapes are urgently needed to improve models of bi-directional exchange. Continued effort in this area is encouraged.

2.12 The program to develop mass-balance estimates of urban GHG emissions is unique and should be expanded to other areas through development of partnerships with state environmental agencies.

2.13 Much of the work on surface atmosphere exchange of reactive trace gases and particles is relevant to efforts by the National Atmospheric Deposition Program to advance understanding of total atmospheric deposition to support ecosystem exposure assessments. Some NOAA ARL staff participate in and hold leadership positions within NADP but wider engagement among other ARL staff is encouraged.

2.14 The breadth of the SAE research program is impressive, and the individual elements are successful. However, the level of coordination across research efforts was in some case unclear (e.g., aircraft work and ground-based reactive chemical fluxes). Perhaps some efficiencies could be gained through closer coordination and strategic planning among teams.

Research Area: Atmospheric Transport and Dispersion (Lead Reviewers: Erik Kabela, Astrid Suarez-Mullins, Susan O'Neill)

Brief Summary

ARL scientists perform activities to understand the main processes that drive the transport and dispersion of harmful substances in the atmosphere, to improve the quality of modeling tools, and to assess the uncertainties and applicability of those tools. In addition, investigations of the transport and dispersion of chemicals in the atmospheric boundary layer serve to provide quantitative flow-visualization information that can lead to new insights and improvements in weather modeling. Focus areas include transport and dispersion (i.e., HYSPLIT), model evaluation, intentional tracers and tracers of opportunity, and mitigation of greenhouse gas (GHG) emissions.

These ARL themes align well with the OAR goals in several areas, including increasing the ability to access and use Earth system data (e.g., GHG emissions), develop interdisciplinary Earth system models (e.g., modeling, model evaluation/tracers), design tools and processes to forecast high-impact weather, water, climate, ocean, and ecosystem events (e.g., modeling, model evaluation/tracers), and transition science that meets users' current and future needs (e.g., modeling, GHG emissions, model evaluation/tracers).

Quality

ARL ATD is a leader in developing or contributing to data streams with high impact to society. They continually update the database associated with the HYSPLIT READY webpage, supporting millions of model runs per year. They also develop and maintain the DATEM webpage and database, which are foundational to system evaluation. They conduct daily WRF meteorological forecasts over domains to support emergency response needs of the Nevada and Idaho facilities. The work improving emission data streams, especially for extreme/episodic events such as wildfires and volcanoes, is applicable now and in the future for the unified modeling system.

The models, tools, and approaches employed by ARL are clearly state-of-the-art in terms of quality. As computational capabilities and new insights develop, there is always room for continual improvement and there is a need for continuous support for innovation.

HYSPLIT is a state-of-the-science tool that is used for many different applications wherein dispersion and its uncertainty are critical. This modeling system is well documented and supported by ARL staff.

The quality of the research and products undertaken in this area are outstanding. The HYSPLIT team listens to feedback from the user community and strives to incorporate new features that are requested. They have a diverse field of collaborators, spanning from applied and operational partnerships to basic research collaborations. The feedback from stakeholders was very positive, and NOAA ARL (specifically ASMD) need to continue to foster these relationships while also exploring collaborations with DOE National Laboratories.

ARL and in particular the Atmospheric Transport and Dispersion (ATD) research area demonstrates scientific innovation and novelty through several breakthrough advancements (e.g., inverse modeling of emissions from multiple emission sources, transfer coefficient matrix). The ensemble work is critical to quantifying both the natural variability of our ecosystems and inherent uncertainty in our parameterizations so that our various realizations of results are in perspective of all the possible answers. The group is commended on the quality and novelty of their work and highly encouraged to continue work in all these areas.

ARL scientists are creating products that not only represent breakthrough advancements in atmospheric dispersion science, but they are also perceptive in how they are charting their course in the complex world of air quality and atmospheric modeling, with many perhaps competing perspectives.

ARL scientists have a long history of ensuring that their scientific developments are sound, accurate, and reproducible through comprehensive evaluations at multiple levels, from unit testing (newly implemented in these past 5 years) to system-wide tracer experiment evaluations.

The ATD also implemented a new code version control system and are investigating cloud computing, which is very promising because standing up a new server can be accomplished in hours not months.

One-on-one with Stakeholders is excellent and the HYSPLIT workshops/training are excellent, reaching 100's of people internationally.

The inverse modeling, transfer coefficient matrix, and ensemble modeling and analysis are all very innovative and excellent.

The Laboratory does an outstanding job documenting scientific objectives. One major kudos I want to give to ARL is the great lengths they have gone to in regard to version control, QA/QC, and other documentation.

Relevance

Research in this area achieves key aspects of the NOAA mission. ARL ATD research is strongly linked to the NOAA Vision Area 1 to reduce societal impacts from hazardous weather and other environmental phenomena and Vision Area 3 of a robust and effective research, development, and transition enterprise. The ATD work achieves key aspects of the NOAA mission by developing systems to address wildfires, volcanoes, and radionuclide emissions, transport and dispersion, and creating innovative ways to improve calculation and delivery of results such as with the transfer coefficient matrix. These developments are effectively transitioned to operations to help reduce societal impacts from these phenomena. The ATD process/emphasis of transitioning projects to operations illustrates the robustness required in Vision Area 3. ARL ATD also achieves key aspects of NOAA's mission to research, develop, and transition results so they are useful to society. Examples of this are the transitions of HYSPLIT nuclear, wildfire, volcano, and chemical applications for emergency response supporting the Comprehensive Nuclear-Test-Ban Treaty Organization (CBTBO), Volcanic Ash Advisory Centers (VAACs), EPA, DoD, DOE, and NWS.

ATD research in this area is clearly linked with ARL and OAR goals. The ARL Strategic Plan clearly shows how each of the three ARL Science Themes align with OAR Strategy Goals. The ATD research theme aligns with OAR goals to detect changes in the ocean and atmosphere by increasing the ability to access and use earth system data (goal 2.3) by adapting their source attribution work to the Fukushima accident and in future work supporting the COP21 agreement. The ATD research theme also aligns with the OAR goal to make forecasts better (goals 3.1, 3.2, and 3.3.) through their modeling work with episodic sources, tracer experiments, and model evaluation. It also appears that the work of ARL ATD is related to OAR goal 4 to drive innovative science and the application of innovative science, such as the work with ensembles, emission inversions, data assimilation, and transfer coefficient matrix.

The one-on-one engagement with stakeholders is excellent and indicative of the relevance of ARL research to a wide user community. ARL personnel work with Stakeholders to improve the systems and transition them to operations. This operationalizing would not be possible without close collaboration and responsiveness to Stakeholders. All Stakeholders commend the Lab regarding their responsiveness and willingness to work with them answering detailed questions and making changes/improvements quickly to address their needs.

Performance

Annual performance and publication targets are met and exceeded.

The number of publications cross-referenced with the Stein et al. HYSPLIT paper from BAMS is amazing. As new major updates become available to the user community, I would encourage the HYSPLIT team to publish an updated article.

Numerous technologies transferred from research to operations/application and assessment shows transformational impacts. Individually, there were 25 developments transferred to operations, and many of these were summarized in four major systems that were transferred for Emergency Response applications including wildfires, volcanoes, nuclear testing/releases, and chemical spills, supporting key partners such as the CBTBO and VAACs.

The Laboratory is efficient and effective and does well with transitioning research to applications.

Targets and milestones in AOP are challenging and are met or exceeded in most cases. ARL meets and exceeds expectations with quarterly and annual targets consistently met and often exceeded as shown in the AOP. It was difficult to assess whether Lab performance advances NOAA goals beyond expectations.

The lab/program maximizes strategic planning to drive results. Serves as a model for other organizations.

ARL has been responsive to recommendations from the previous review in the ATD research area.

Recommendations for this Research Area

3.1 ARL should continue to invest in the development of the HYSPLIT model (e.g., parametrization, numerics) and the integration of new and relevant capabilities into the modeling system (e.g., STILT, TCM).

3.2 Efforts related to inverse modeling and developing refined emission estimates for wildfire and time-height resolved volcanic emissions are extremely useful and have broad applications beyond those of ARL. Making these emission data sets publicly available for broader use is recommended.

3.3 Closer integration of research efforts by the HYSPLIT and NAQFC groups could help in development of a more cohesive research program. In particular, the use of refined emissions from HYSPLIT based inversion methods (for select sectors) in the NAQFC should be tested.

3.4 Improvements in memory usage and parallelization of the HYSPLIT code are needed to allow for time steps less than one minute to accommodate higher resolution (e.g., sub-kilometer, urban modeling) runs. Alternative strategies to address resourcing deficiencies with HPC and cloud computing (e.g., leveraging external HPC for research and development efforts) should be explored. These improvements will make HYSPLIT more scalable.

3.5 Capability to generate meteorological fields using only observed meteorology from surface-based, profiling instruments, etc. is needed. This can be done now by assimilating observations into WRF, running WRF, then post-processing the WRF file for HYSPLIT usage. Being able to generate a 4D, mass-consistent meteorology field using only observations and having the result available relatively quickly would enhance HYSPLIT capability. I believe a version of this capability exists with HYRAD (developed at NOAA ARL FRD) but allowing this capability out to the user community could really aid in further development.

3.6 Capability to process more than 12 meteorological files for a HYSPLIT run is needed.

3.7 Continuing to incorporate more software engineering principles into HYSPLIT (and other) codes is encouraged.

3.8 ARL should leverage collaborations with the international community to increase its repository of tracer data and to further its model verification, uncertainty estimation, and data assimilation efforts.

3.9 Continued work in the areas of inverse modeling, the transfer coefficient matrix, ensemble modeling and analysis, and gaussian mixture method is strongly encouraged.

3.10 Ensure robust version control and FAIR principals are followed for all publicly facing products (in particular HYSPLIT) to enable reproducibility of analyses performed by users.

3.11 Consider hosting an annual HYSPLIT user-group conference to facilitate exchange of ideas, sharing of research results, and further cultivation of community-based user support. This would further enhance the utility of HYSPLIT.

3.12 ARL should more effectively leverage social media networks to engage with the scientific and technical community and to promote HYSPLIT developments, scientific publications, and/or other breakthroughs.

3.13 Consider a quarterly HYSPLIT newsletter noting recent updates, publications, and summary of important topics discussed in the existing HYSPLIT user forum. Encourage the use of the online Forum to get questions answered when a new release is made. When a new HYSPLIT release is made, have short online videos or tutorials for users to learn more about the new options. Ex. STILT, Sofiev plume rise.

3.14 Consider how to internationalize the user base and applications of the models and insights developed by this group. How can the models and tools be more broadly applied in service to global society? Possibilities to engage users outside N. America via workshops, WMO, etc. could be explored.

3.15 All ARL team members appear to make the effort to present at conferences, which is great. For wildfire related work, I recommend targeting conferences where wildland fire smoke is a focus such as:

- Wildland Fire Canada Conference, Oct 31-Nov 4, 2022, Edmonton, Canada
- International Association of Wildland Fire (IAWF), Fire and Climate Conference, May 2022, Pasadena, California.
- International Smoke Symposium (every three years)
- AMS Fire and Forest Meteorology (every three years)
- Other IAWF conferences such as the Fire Behavior and Fuels Conference. These conferences often have an international component, such as a dual US/Australia conference.

Research Area: Boundary Layer Characterization (Lead reviewers: Dave Turner and Peter Thorne)

Brief Summary

ARL conducts research and monitoring to improve understanding of boundary layer processes using a suite of short- and long-term measurements. Focus areas include continental-scale monitoring of climate variables (U.S. Climate Reference Network), mesonets in urban and rural landscapes, the use of small-uncrewed aircraft systems (SUAS) to characterize boundary layer conditions, and instrumented supersites to investigate land-atmosphere exchange in complex terrain.

These efforts support and are relevant to OAR strategic goals to identify and address gaps in observation requirements needed to understand causes of variability and change in the oceans and atmosphere (mesonet and SUAS), increase ability to access and use Earth system data (SUAS and long-term measurements), and accelerate the delivery of mission-ready, next-generation science (SUAS and long-term measurements).

Quality

The suite of observation programs, many undertaken on a sustained basis, are a highly valuable contribution to both national and international science. The programs are designed and maintained to high standards as evidenced by the range of end-user applications, particularly so for USCRN.

The USCRN is providing critical data to understand surface layer processes over a wide range of climatically relevant locations.

The teams focused on this research area are doing exemplary work. Specifically, I'd like to call out SORD. They are doing great work in attempting to consolidate and streamline operations between the two division offices in Nevada and Idaho. The high quality of their work is expressed by stakeholders.

ARL's strength is looking at lowest 300 m, which is ideal for studying land-atmosphere interactions.

Excellent work on building surface layer parameterizations and studying flux/profile relationships over a range of atmospheric conditions needed to build these parameterizations.

ARL's leadership in organizing and executing cross-laboratory workshops and field campaigns (e.g., CHEESEHEAD, SPLASH) to coordinate research on the boundary layer is excellent.

Performance

The USCRN is considered one of the best surface layer observation networks in the world, and these observations are used by a range of different scientific communities.

I find the Laboratory performs at the highest level in terms of how relevant they are to the current and future needs of end users.

The measurements and analyses answer a variety of key scientific questions. The programs are clearly directly responsive to a range of stakeholder needs.

Relevance

UAS observations have the potential to be extremely impactful in a wide range of research, from better characterization of the thermodynamic and kinematic structure of the boundary layer, to providing information on the spatial homogeneity of surface fluxes, to airborne observations of trace gases and aerosols. ARL is helping to lead that effort to develop improved UAS sampling strategies and products within OAR.

The work that ATDD is doing with UAS could be great for the future of weather "nowcasting" with the ability to be able to take measurements vertically and horizontally in a small environment, then feed this information to decision makers or have it available for ingestion into models.

SORD does a great job with supporting their customers at the NNSS. Further, I believe enhancement of the capabilities (modeling and instrumentation) and research at SORD-ID is ongoing and should continue down a collaborative path with DOE national laboratories.

Impressive continuity of programs across the covid-19 pandemic despite evident challenges. A number of relevant and high-quality publications produced.

Recommendations for this Research Area

4.1 Consideration should be given to addition, including retrospective reprocessing, of metrologically quantified uncertainties to USCRN primary measurement series to increase potential applications of these data. Work on temperature undertaken by UK NPL colleagues should be reviewed and operationalized. Similar work should be undertaken on remaining primary variables.

4.2 A subset of USCRN should be put forward for the new Global Surface Reference Network once progress has got that far. NOAA ARL should continue active engagement in the process of setting up the GSRN.

4.3 USCRN must be maintained for decades and hence this will require increases in funding, at a minimum to account for inflation impacts, moving forward to avoid placing aspects of the program under undue stress. Both personnel and material costs will increase with time and the base funding request must rise accordingly if USCRN is to be maintained to the highest standards.

4.4 USCRN expansion throughout Alaska, understandably delayed by the pandemic, should be completed within the next review period.

4.5 The work using new boundary layer techniques should be expanded to consider underrepresented complex/challenging environments where present flux behaviors are most poorly known (e.g., open water, coastal and topographically complex regions) and in particular, deployments should prioritize those environments not amenable to fixed instrumentation. For example, IPCC AR6 WGI highlighted the criticality of understanding ocean-atmosphere fluxes across globally representative ocean zones and across the seasonal cycle. Via cooperation with other line offices and federal agencies, as well as international partners, scope for use in these contexts would be valuable.

4.6 ARL needs to push their BL profiling capabilities and datasets higher into the PBL, ideally up to the top of the PBL. This may require working more closely with other OAR labs to develop expertise in remote sensing technology.

4.7 ARL should continue to pursue UAS research and look for ways to expand.

4.8 SORD does a great job supporting their customers at the NNSS and should develop collaborations with entities such as DOE national laboratories. This could involve convening information sessions with representatives from DOE laboratories to find avenues for collaboration.

4.9 While resources are understandably limited, opportunities to expand DCNet to other urban areas should be explored. Such measurements can serve as a focal point for integration of atmospheric monitoring in urban areas, e.g., coordination with air quality networks. ARL seems well positioned to be leaders in this area.

4.10 Support for efforts to better understand boundary layer processes in complex natural landscapes should continue. Among other applications, such datasets are needed to improve the ability of models to simulate land-atmosphere exchange processes in pristine environments with complex topography, e.g., high elevation Class I wilderness areas, where uncertainty in model predictions of ecosystem exposure to atmospheric deposition is high.

Comments and Recommendations Regarding the Review Process

Overall, the panel felt that this review was very well organized by ARL staff. The level of effort to prepare the panel members and provide high-quality, well-organized review materials is impressive and appreciated.

What worked well:

- I appreciate that ARL leadership made it easy for an outside reviewer to clearly understand how ARL is strategically aligned with the parent OAR and NOAA visions/missions.
- Communication between ARL administrative staff and review panel
- Having all of the materials in a well-organized central location (i.e., webpage)
- Availability of review materials several weeks before the meeting
- Access to the recorded presentations
- Stakeholder and post-doc/CI staff sessions
- Building awareness of OAR's perspective/objectives early in the process during pre-review meetings

What could be improved:

- Reconvene in-person reviews as soon as possible
- Provide funding information in mission overview briefing, including a breakdown by portfolio
- Provide early access to the mission overview briefing along with all other materials
- Provide a summary of self-identified gaps to meet mission objectives (e.g., resourcing) and current mitigating strategies

- Provide more time for Q/A with ARL technical and scientific staff
- Request stakeholder's responses to be given informative file names (e.g., stakeholder response_Last_First_Organization) to promote organization and easy identification
- It would have been useful to have a discussion with federal staff who are not in the leadership team as we did not have an opportunity to informally discuss with them their views in general upon the lab, career opportunities, etc. and therefore other than scientifically they were voiceless in the process.
- Time for one-on-one interactions with scientists on individual projects would be useful (similar to the time set aside for interactions with post-docs and cooperative institute staff).
- One note for future reviews is that I did not see whether a process is in place to evaluate projects based specifically on meeting the strategic plan. Adding that clarity to the information provided would be helpful.

Appendix: Full List of Recommendations

Recommendations for the Laboratory

1.1 ARL should supplement its strategic plan with prioritized thrust areas that consolidate complimentary research objectives across the Surface-Atmosphere Exchange, Atmospheric Transport and Dispersion, and Boundary Layer Characterization program areas.

1.2 Though the diversity of projects that ARL staff contribute to is impressive, in some instances the level of involvement was not apparent. While this may be a consequence of changing stakeholder needs, in the long-term some balance between fulfilling short-term stakeholder needs and building an anticipatory research program that cultivates the lab's core capabilities may be desirable. Where possible, OAR and ARL management should seek opportunities that also help with the formulation of anticipatory research.

1.3 ARL should prioritize the modernization of the HYSPLIT code and web-based functionalities to ensure portability and adequate (or enhanced) performance in emerging computational platforms (e.g., HPC, cloud, GPUs). To enable these efforts, ARL is encouraged to continue to identify and inject its infrastructure needs into OAR strategic planning.

1.4 ARL needs to update its websites and improve data repositories to make them more accessible (e.g., improved APIs, discoverability, and metadata). This was a common suggestion for improvement among stakeholders.

1.5 There is concern about program continuity, as it seems some ARL programs are led by a single federal staff member (with several nearing retirement age). ARL should actively work to build redundancy of expertise in scientific and technical areas that could be affected by retirements in the near term. The development of a strategic plan to address gaps resulting from lack of redundancy due to talent attrition (e.g., retirements, promotions, lateral moves) should be pursued.

1.6 The extended use of “acting” roles within the ARL ranks, especially leadership roles, is troubling. OAR should prioritize completing all hiring actions for ARL leadership staff.

1.7 The precarity of non-federal positions and declining federal workforce present medium to long-term risks. While there is a role for contractors and cooperative institutes, they should be value-added and not critical to core mission aspects. As such, efforts should be undertaken to convert posts where possible to federal positions.

1.8 International engagement is principally in the form of committees and working groups with little evidence for sustained collaboration with international partners, particularly outside North America. This risks under-exploitation of the useful tools and approaches developed by the lab. An international engagement strategy would be valuable. Long-term win-win partnerships should be sought which may increase support either directly or through in-kind collaborations. Examples exist such as the collaboration between NOAA NCEI and C3S on collection and management of global in-situ data holdings.

1.9 Principal reported conference engagements were at AGU and AMS. While these are undoubtedly valuable and have high visibility, more specialized conferences and workshops on focused topics (e.g., fire) are oftentimes more valuable in terms of networking and gaining insights and engagement. A more balanced portfolio of meetings attended may yield dividends and better community engagement. Consideration should also be given to attendance at relevant international meetings to broaden impact.

1.10 ARL is to be commended for its mentoring and outreach efforts. However, ARL should continue to develop and provide leadership opportunities to its female scientific staff.

1.11 ARL should actively engage users in DOD, DOE, and other US government organizations to identify opportunities for collaboration, including classified applications. To facilitate these efforts, a greater number of staff members with clearances might be needed.

1.12 ARL should invest into growing support staff for the HYSPLIT model to better balance research and development efforts with ever-growing operational support requirements, including code dissemination and management, user training, and real-time support (e.g., READY).

1.13 ARL's plans for the advancement of atmospheric transport and dispersion applications appear well aligned with user community needs and requirements. The organization is encouraged to pursue these very critical topics fully.

1.14 ARL should explore opportunities to align its current efforts in urban air quality research to more directly address environmental justice issues. ARL seems very well positioned in this regard.

Surface-Atmosphere Exchange

2.1 Development and testing of the air quality components in the UFS framework should be continued as they often help identify issues related to transport and conservation that may not be diagnosed through NWP applications alone. It appears that some representation of the large-scale forcing beyond the current GEFS-GOCART system may be needed to capture changes in global emissions and their impacts on long-range pollution transport to North America. Development of a low resolution UFS-CMAQ system for creating space and time varying chemical lateral boundary conditions or use of other systems (e.g., Copernicus) could be explored.

2.2 Migration of the NACC code to the AWS platform to expand userbase for the FV3GFS-CMAQ for other regional domains across the globe is a worthwhile activity and should be continued.

2.3 ARL invests significant effort in creating emission data sets to drive the NAQFC system and in the future may be pursuing similar efforts on the global scale for the UFS. Documenting the changes in these data sets (for instance relative to the NEI for the U.S.) and making them publicly available may help increase their utility and promote transparency in the overall forecast products.

2.4 In many instances it seems that opportunities exist to broaden the utility and impact of ARL's research and development activities:

(iv) Several examples were presented where ARL research led to development of new emission data sets for select species (e.g., CH_4 for Maryland, Volcanic SO_2) or sectors (wildfires in the future). These data have broad potential use and should be made publicly available for use by the broader scientific community, which would help promote ARL and NOAA's research efforts.

(v) The initiation of collaboration between ARL and GFDL to apply the SEBN data for evaluation and improvement of land-surface models is a positive development. Similar collaborative efforts where ARL measurements can help inform development of scale-aware processes in earth system models should be actively pursued and encouraged.

(vi) Long-term Hg measurements provide unique opportunities to assess and contrast trends in Hg speciation and possible shifts in seasonal behavior across different locations (background, suburban, Arctic) and serve as useful tests for models. Continued analysis of this nature and collaboration with modeling groups should be pursued.

2.5 New collaborations (e.g., with DOE's Atmospheric System Research program) would provide additional opportunities and datasets to improve air quality model (NAQFC) and should be encouraged.

2.6 Consider viability of expansion of the SEBN network to have a permanent presence in Alaska to monitor the rapidly changing Arctic climate, preferably paired with a USCRN site.

2.7 A contingency plan is required for if UFS leads to unacceptable degradation of model-based applications. Is there a formal lock on UFS release depending upon implications for the composition models? If not, is there a fall-back plan for continuity of existing products unless and until acceptable (comparable or better) performance than existing systems can be found?

2.8 Setting up a research version of a low resolution global UFS-CMAQ system for creating space and time varying chemical lateral boundary conditions for regional NAQFC could help explore possible impacts of changing large-scale forcing and global emissions on daily air quality forecasts and provide guidance for evolution of the operational system.

2.9 ARL efforts to apply multi-layer models to better understand in-canopy processes influencing net canopy-scale fluxes of reactive gases and aerosols is unique relative to other agencies and academia and should be continued.

2.10 Development and application of large eddy simulation as a tool to better understand surface-atmosphere exchange processes is encouraged, particularly for deep canopies and complex environments.

2.11 Direct measurements of surface-atmosphere exchange of ammonia and relevant biogeochemistry/surface conditions in natural and agricultural landscapes are urgently needed to improve models of bi-directional exchange. Continued effort in this area is encouraged.

2.12 The program to develop mass-balance estimates of urban GHG emissions is unique and should be expanded to other areas through development of partnerships with state environmental agencies.

2.13 Much of the work on surface atmosphere exchange of reactive trace gases and particles is relevant to efforts by the National Atmospheric Deposition Program to advance understanding of total atmospheric deposition to support ecosystem exposure assessments. Some NOAA ARL staff participate in and hold leadership positions within NADP but wider engagement among other ARL staff is encouraged.

2.14 The breadth of the SAE research program is impressive, and the individual elements are successful. However, the level of coordination across research efforts was in some case unclear (e.g., aircraft work and ground-based reactive chemical fluxes). Perhaps some efficiencies could be gained through closer coordination and strategic planning among teams.

Atmospheric Transport and Dispersion

3.1 ARL should continue to invest in the development of the HYSPLIT model (e.g., parametrization, numerics) and the integration of new and relevant capabilities into the modeling system (e.g., STILT, TCM).

3.2 Efforts related to inverse modeling and developing refined emission estimates for wildfire and time-height resolved volcanic emissions are extremely useful and have broad applications beyond those of ARL. Making these emission data sets publicly available for broader use is recommended.

3.3 Closer integration of research efforts by the HYSPLIT and NAQFC groups could help in development of a more cohesive research program. In particular, the use of refined emissions from HYSPLIT based inversion methods (for select sectors) in the NAQFC should be tested.

3.4 Improvements in memory usage and parallelization of the HYSPLIT code are needed to allow for time steps less than one minute to accommodate higher resolution (e.g., sub-kilometer, urban modeling) runs. Alternative strategies to address resourcing deficiencies with HPC and cloud computing (e.g., leveraging external HPC for research and development efforts) should be explored. These improvements will make HYSPLIT more scalable.

3.5 Capability to generate meteorological fields using only observed meteorology from surface-based, profiling instruments, etc. is needed. This can be done now by assimilating observations into WRF, running WRF, then post-processing the WRF file for HYSPLIT usage. Being able to generate a 4D, mass-consistent meteorology field using only observations and having the result available relatively quickly would enhance HYSPLIT capability. I believe a version of this capability exists with HYRAD (developed at NOAA ARL FRD) but allowing this capability out to the user community could really aid in further development.

3.6 Capability to process more than 12 meteorological files for a HYSPLIT run is needed.

3.7 Continuing to incorporate more software engineering principles into HYSPLIT (and other) codes is encouraged.

3.8 ARL should leverage collaborations with the international community to increase its repository of tracer data and to further its model verification, uncertainty estimation, and data assimilation efforts.

3.9 Continued work in the areas of inverse modeling, the transfer coefficient matrix, ensemble modeling and analysis, and gaussian mixture method is strongly encouraged.

3.10 Ensure robust version control and FAIR principals are followed for all publicly facing products (in particular HYSPLIT) to enable reproducibility of analyses performed by users.

3.11 Consider hosting an annual HYSPLIT user-group conference to facilitate exchange of ideas, sharing of research results, and further cultivation of community-based user support. This would further enhance the utility of HYSPLIT.

3.12 ARL should more effectively leverage social media networks to engage with the scientific and technical community and to promote HYSPLIT developments, scientific publications, and/or other breakthroughs.

3.13 Consider a quarterly HYSPLIT newsletter noting recent updates, publications, and summary of important topics discussed in the existing HYSPLIT user forum. Encourage the use of the online Forum to get questions answered when a new release is made. When a new HYSPLIT release is made, have short online videos or tutorials for users to learn more about the new options. Ex. STILT, Sofiev plume rise.

3.14 Consider how to internationalize the user base and applications of the models and insights developed by this group. How can the models and tools be more broadly applied in service to global society? Possibilities to engage users outside N. America via workshops, WMO, etc. could be explored.

3.15 All ARL team members appear to make the effort to present at conferences, which is great. For wildfire related work, I recommend targeting conferences where wildland fire smoke is a focus such as:

- Wildland Fire Canada Conference, Oct 31-Nov 4, 2022, Edmonton, Canada
- International Association of Wildland Fire (IAWF), Fire and Climate Conference, May 2022, Pasadena, California.
- International Smoke Symposium (every three years)
- AMS Fire and Forest Meteorology (every three years)
- Other IAWF conferences such as the Fire Behavior and Fuels Conference. These conferences often have an international component, such as a dual US/Australia conference.

Boundary Layer Characterization

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