

**Report of the Review of the  
NOAA  
GLOBAL MONITORING LABORATORY  
21-23 October 2024  
Review Panel**

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## **1. Overview & Background**

In October 2024, NOAA Research commenced a 5-year cadence of reviews of their laboratories, beginning with the Global Monitoring Laboratory (GML). This review is performed to assess GML's effectiveness in meeting NOAA's mission, NOAA's research and observational priorities, and quality of their work/research.

Presentations to the review committee centered around 5 questions and were organized by the 3 primary research themes of GML. The questions were:

1. GML has been pursuing research under the three main research themes (Tracking Greenhouse Gases and Understanding Carbon Cycle Feedbacks, Guiding Recovery of Stratospheric Ozone, and Monitoring and Understanding Trends in Radiation, Clouds & Aerosols). Is the information provided by GML under these themes relevant and appropriate for diagnosing key aspects of Earth's climate system, for reducing uncertainties within it, and for addressing societal challenges associated with a changing climate?
2. Are the three supporting pillars within GML (Sustained Observations, Standards, Technological Innovation) well structured and resourced, allowing GML to continue making progress towards reaching its strategic objectives?
3. Are GML's datasets easily findable, accessible, interoperable, and reusable, and its data products relevant for stakeholders? Are the data management activities optimally organized?

4. What are potential solutions and strategies that GML should explore as part of its efforts to enhance its current capabilities and create routine, reliable, and robust greenhouse gas (GHG) monitoring and information systems in a sustainable manner to address national and international needs for GHGMMIS (GHG measurements, monitoring and information systems)?
5. GML has made progress in recent years in improving the diversity of our workforce. What other actions are recommended to accelerate further progress in building a diverse workforce that is more representative of the U.S. workforce population? How could GML more effectively integrate participation from diverse communities and disciplines and enable our research to more directly benefit society in addressing challenges associated with climate change?

This report is organized roughly by the 5 questions we were asked to consider for this review, followed by findings and recommendations. The research themes are specifically addressed in the first two questions. Each individual on the review panel has submitted their reviews, and these findings borrow appropriately from the 6 individual reviews. It is not a consensus review summary, but a synthesis report to capture the common findings of the individual reviews and to highlight the most prominent findings.

## **2 Summary on Questions**

### **2.1 Appropriateness of the GML themes within NOAA's mission**

All three themes focus on important science topics where observations are required for monitoring changes in the Earth system. GML observations in these areas have occurred over sufficient time scales for assisting the science community in answering key questions regarding Earth system changes. Because of the need to monitor newly discovered gases and pollutants, they also have been at the technological innovations forefront. GML's long-term measurements and calibration activities, providing data that the global community depends on and trusts, are of the highest relevance and quality. There are other areas where long-term observations would be useful to the science and policy communities, some of which were previously GML themes (i.e. air quality), but given available GML resources, the correct choices were made. There are few other scientific institutions globally with the scientific leadership, expertise, and facilities that can provide these observations and associated analyses.

Prediction is mission-critical for NOAA, so it is important to assess GML's work in this context. How monitoring and sustained observations advance better process understanding and integration with models for improving prediction was not well articulated in the presentations. It is typically assumed that monitoring data is not used well for process studies, but with the appropriate collection of measured properties, long-term monitoring can shed light on large-scale processes that detailed, focused field campaigns cannot address.

NOAA Research does not generally assess cross-lab work in their 5-year reviews, which puts the organization at a disadvantage in achieving its goals. Each of the labs is filling a unique space and their work should move in concert to address NOAA

Research's priorities. The lab's work to prioritize and shape their own work in a resource-limited environment would also benefit from a more strategic look at the OAR and other higher-levels in NOAA. Ideally this would make clear how GML's work aligns with, and serves as the foundation of, NOAA's Climate Value Chain.

Since the last GML review, OAR leadership is much more aware of the research output from GML and has a better understanding that the lab is not solely operational and collectors of data. Emerging research opportunities (e.g., expanding the connection of the atmosphere and ocean) was done well for carbon and GHGs, but was not mirrored as much in radiation/aerosol/clouds and stratospheric ozone work.

### **2.1.1 Theme 1: Tracking Greenhouse Gases and Understanding Carbon Cycle Feedback**

GML has a clear and sustained record for producing *quality* data and analyses that have advanced understanding of GHG trends and carbon cycle feedbacks. Their work is highly relevant both to the global research community and also to address policy, as evidenced through use by other US government agencies such as the EPA. Improving understanding of transport processes is a potential future activity. Other parts of GML (Theme 2) and NOAA Research (ARL, GSL) have a strong interest in, and measurements for, boundary layer processes so partnerships could help this effort. Another gap that emerges is the study of meso-scale processes and their relationship to synoptic and larger scales. Knowledge could be gained by developing mobile observational systems (that might move across regimes) or collaboration with other groups doing this work, as there are many (e.g., NSF NEON, DOE ARM).

The resource level for modeling efforts is an important GML decision. An in-house modeling program has clear benefits in sustaining quality measurements and their interoperability for various applications. While modeling can support monitoring and analysis primary goals, the GML modelling goals need prioritization (develop new observations? new sampling strategies? observations interpretation?). What does GML need internally, and where can it partner?

GML is already using OSSEs to guide needs, which is commended. Model improvements will also improve OSSEs.

### **2.1.2 Theme 2: Monitoring and Understanding Trends in Radiation, Clouds & Aerosols**

The radiation group is known for its high data quality, and it is clear that the group has grown in its research strength and breadth of topics it addressed since the last review. The merger of the radiation and aerosol groups will improve its relevance, particularly if it can successfully integrate measurements to address new topics such as radiative forcing and aerosol-cloud processes. The impacts of the aerosol theme are primarily through providing data for model evaluation, rather than through research on basic physical process understanding. The work presented on linking Dimming & Brightening to global modes of variability is excellent and important, representing an elevation of the group's often more technical research papers. It is highly relevant for understanding

global-scale temperature and pressure patterns, shifts in circulation, and their impact on regional to local-scale cloud and surface radiation budget conditions over decadal timescales. These are key outcomes for improving both understanding and prediction - NOAA's primary objective.

The level of collaboration, both internal to NOAA (GSL, ARL, CSL, PSL for observations and analysis) and external (DOE, international organizations through grants and field campaigns), is evident and enables this group to have an outsized impact. The collaboration with GSL is essential for identifying weather model biases and drivers, and it has grown over time. Also, there is a stronger focus on emerging, relevant applications such as renewable energy and wildfire that are societally relevant. Improvements in these areas will certainly positively impact GML relevance, provided they are sustained.

Potential areas of focus for the future include capitalizing on recent effort in measuring boundary layer properties and collaborations with labs such as GSL, which model and advance understanding of processes in the PBL. By coupling this with SURFRAD in the US and BSRN globally, there is the opportunity to integrate pieces of information that define the regimes and regions where processes are more or less globally, regionally, or locally driven and how that benefits predictability. GML should focus on how they might package information to support operational activities such as NWP. Data products that aggregate multiple direct measurements, higher-level retrievals, or even indices may serve this purpose well.

Two areas where the new merged aerosol and radiation group might find a niche where other agencies are either not set up to focus or have declined to prioritize are:

- Defining the relationship between in situ and remote sensing aerosol measurements and hygroscopicity. This relationship is critical for using the broad spatial coverage of in situ aerosol properties to improve our understanding of aerosol radiative forcing. It could require reshuffling of measurements to get in situ aerosol measurements, water vapor, MFRS Rs, etc. collocated in key aerosol and humidification regimes, but if done routinely in a couple of places there could be a substantial payoff.
- Spectra for aerosol and cloud retrievals. There is information content there and other agencies have largely declined to pursue the space.

### **2.1.3 Theme 3: Guiding Recovery of Stratospheric Ozone**

Stakeholders note that the data quality from this group is consistently high and it is clear that the monitoring of ozone and ozone depleting substances has excelled in detecting violations of the Montreal Protocol and connecting the increases in substances with variations in stratospheric ozone levels. New technologies have made these discoveries possible, so investments in new measurement approaches should continue in order to improve accuracy and sampling in order to keep up with scientific needs. The standards and calibration efforts under this theme are highly developed and critically important to GML's measurements and research, but also to the global community.

As with Theme 2, this theme has expanded its reach through partnering, leveraging the GHG network to expand. Kudos for leveraging existing GML infrastructure to expand the lab's capabilities and impact. The expansion of the surface ozone network is also producing exciting new science.

In addition to consistent monitoring and network expansion, rapid response deployments are helping to track changes in ozone and identifying specific processes driving these changes. GML does not have a strong legacy in studying dynamics and transport, so it should continue this work – specifically, to better understand how processes such as volcanic eruptions, aerosol distribution, and general transport patterns impact ozone – but in partnership with groups that have strong expertise. A fruitful collaboration with CSL has already enabled substantial expansion of water vapor balloon sampling, adding POPS measurements for stratospheric aerosol sampling. As a new effort driven by an emerging application (climate engineering), GML should consider how, and if, it will be sustained in the future. In terms of future planning, GML should also consider how its scientific focus will evolve with personnel changes and ensure that appropriate staff are in place.

Finally, as the U.S. struggles with supporting continuous and comprehensive space-borne measurements, it is even more critical for GML to maintain and expand sampling. These observations provide critical information for informing compliance of international policy and climate prediction, and satellite calibration and validation. These data are absolutely critical in international assessments and reports, which will only grow due to absence in satellite data.

## **2.2 Supporting Pillars of GML**

The activities reported under the three supporting pillars (gas standards, baseline observatories, technology development) are among the most valuable and tip-of-the-spear for global GML's operations of long-term measurements and significantly enhances the quality of the observations made. Because of the high caliber and frequent needs of monitoring newly discovered gases and pollutants, they also have been at the forefront of technological innovations. GML's long-term measurements and calibration activities, providing data that the global community depends on and trusts, are of the highest relevance and quality.

Baseline observatories provide crucial stability to the GML measurements as well as MANY other activities internationally. That latter aspect has major budgetary implications for GML. The observatories are relied upon by so many other non-NOAA funded activities that GML has a significant obligation to continue supporting these observatories. When tough decisions are necessary to maintain these facilities with available resources, the third pillar, technology development, tends to take a hit. This then affects GML's ability to advance their monitoring techniques as new methods emerge and become scientifically necessary.

Many of the new technologies that GML has been pursuing over the past decade have tended to take a decade or more to fully advance due to available investments in those areas. While the panel understands tradeoffs in the decision process for where to apply

available resources, more resources in the technology development would be appreciated by the science community.

Specific findings:

Ozone and water vapor work at GML have been exceptional in the last decade. The regular water vapor sonde launches are unique. When the NASA MLS satellite instrument fails, this will be our best data set for showing long-term water variations. As with the ozone depleting substance (ODS) observations, the ozone and water provide a stable, long-term record. These observations are essential for satellite comparisons and validation. While the Dobson spectrophotometers have provided an amazing long-term record, replacements for these instruments are not being manufactured, threatening a sustained total column ozone record.

The tracking of ODSs has been exceptionally impactful. The identification of the CFC-11 emissions increase was first-rate policy-relevant science, and the Parties to the Montreal Protocol are now in the process of increasing the observational coverage to improve regional emission estimates. Of course, the application of standards to these observations is key to accuracy and precision estimates, which in turn make global emission observations credible. These unassailable standards and observations ensure the seriousness and credibility with which policy makers view the GML data. The lab work on ODSs (as with all of these halogenated species) is of high quality and state-of-the-art science. The ability to diagnose trends in human-produced emissions depends on both the quality and the long-term sustainment of the observations. These trends and changes are key facts for policy makers – fulfilling a principal role for NOAA.

Similarly, the standards for CO<sub>2</sub> are not just the “NOAA Scale”, but have been adopted as the “WMO Scale” and relied upon by all of the international CO<sub>2</sub>-observing programs, even the satellite observations. This is a critical and core service to the entire GHG research community.

The increasingly important facility for solar radiation calibration and its work in coordinating and collaborating with WMO and NIST as well as ~~its not to mention~~ tracking the vast network sites and data spanning all the way back to the 1970s is of high quality and irreplaceable.

GML scientists are highly cited and involvement in monitoring water vapor and ozone, partnership with United Airlines to study pollution with high-tech sensors, and tracking the benefits of the Montreal protocol, not to mention the annual product releases, are visible and high-quality accomplishments.

### **2.3 Data management and distribution of GML produced data sets**

GML has extraordinary datasets that are EXTREMELY relevant to stakeholders, representing unparalleled generations of information associated with climate change. These datasets are some of the most valuable pieces of information in the world for recording, diagnosing, and mitigating climate impacts and environmental change. They are also valuable for improving weather forecasting, the efficiency of renewable energy,

and other more immediate applications. Their value and uniqueness stem in part from their long, continuous temporal record, maintained at high quality to track changes over time associated with global environmental change.

While GML's data are well-used within its traditional user community and in traditional ways (especially the international over the national community), its delivery system and data publicizing are not up to modern standards. Generally, the data are findable, interoperable, and reusable in the traditional sense of these words for humans through the local distribution site. However, GML's framework for data distribution does not conform to many of the FAIR (findable, accessible, interoperable, and reusable) principles that enable machine-actionable structures. This disadvantages the lab and NOAA in achieving the desired impact of these data, as well as the impact commensurate with the investment.

The data web site is confusing with obsolete plots, older formats, and a non-centralized data distribution. As noted by one stakeholder, "Data sites are creaky and use obsolete, idiosyncratic data formats ." Other stakeholders referred to GML's data services as "awkward", "archaic", and "not scalable." A quick GML web site perusal identified a variety of data issues:

- Some datasets not up to date: E.g.,  $\text{NF}_3$   
[https://gml.noaa.gov/aftp/data/hats/PERSEUS/NF3\\_PR1\\_MS\\_flask.txt](https://gml.noaa.gov/aftp/data/hats/PERSEUS/NF3_PR1_MS_flask.txt)
- All data shown in figures (i.e., data visualizer pages) should be also available for download in the Data Portal. E.g., global/NH/SH averages of  $\text{CCl}_4$ . See:  
<https://gml.noaa.gov/hats/combined/CCI4.html> The files should be consistent with what is found in the data portal: <https://gml.noaa.gov/data/data.php?search=ccl4>  
The global and hemispheric averages are not found in the data portal, but are shown in:  
<https://gml.noaa.gov/dv/iadv/graph.php?code=MLO&program=hats&type=ts>
- Many plot web pages are not up to date and inconsistent across the web site: See top figures in <https://gml.noaa.gov/hats/graphs/graphs.html>. The  $\text{CCl}_4$  data only extend through 2012, while a lower plot extends to 2019. In fact, there are four  $\text{CCl}_4$  plots vs. time on this page. The  $\text{CCl}_4$  in the <https://gml.noaa.gov/hats/data.html> site runs to about the end of 2022, while the site: <https://gml.noaa.gov/hats/combined/CCI4.html> runs through 2023.
- The data viewer is good, but it should have a "data download" link. E.g., the  $\text{SF}_6$  plot (<https://gml.noaa.gov/dv/iadv/graph.php?code=SPO&program=hats&type=fi>) should have data links. Checking for  $\text{SF}_6$  in the data portal, the MCM (McMurdo) site for  $\text{SF}_6$  data was not findable.
- The data portal should also include an "observations date range" column.
- NEDCDF should be the primary data format option with ASCII files as backup. Also, the metadata is thin.

While GML is a primary source of observations and data analyses, the linkages to other data providers are weak. Stakeholders noted that communications with data providers for the “ObsPack” ought to be enhanced, especially for those data sets not currently included. For example, while the scientist-to-scientist connections between GML and AGAGE are strong, there are no formal links, references, or acknowledgements on the GML web site to this other source of information (and maybe vice-versa too).

While some data are used in highly developed products or tools for the community, such as CarbonTracker and AGGI, not all of the important data sets have associated tools that enhance their reach and impact. Stratospheric aerosol, a hot topic currently being studied and measured within NOAA and GML, is an example. However, the MLO transmission data does not have an annual release comparable to some GHG measures.

Meeting FAIR principles is essential for better transitioning data to use, especially in today’s environment of automated machine-use of data, AI/ML, and general data-driven approaches to prediction (e.g., radiation data for solar energy forecasting), and growing integration of models and observations for a range of applications. NCEI is the official repository for GML data, but the goal is to develop the GML data archive, since most users currently access it. However, this approach may result in duplication of offerings and efforts, which could be counterproductive for increasing use and impact, and may waste resources. GML can more effectively point to official and well-supported archives, leveraging the support and technical expertise.

**Quality:** High

Stakeholders noted specifically and frequently that the quality of GML data is very high. The lab’s associated standards and calibrations programs along with each group’s quality control and management processes provide the environment to maintain this high quality. Leadership, participation, and coordination with national and international networks and data archives with their own criteria for membership, e.g., BSRN, also add to the maintenance of data quality measures.

**Relevance:** High

Many of GML’s data products are exceptionally relevant as evidenced by their use in publications, including national and international assessments, use metrics, and attestations of stakeholders. However, GML maintains many datasets so it is difficult to determine whether all that are supported hold the same value. A structured, lab-wide usage metrics program would provide valuable information for prioritization exercises.

**Performance:** Moderate

**FAIR evaluation:**

**Findable:** low. GML’s datasets are not extensive, so browsing through the archive interface does allow for identification of datasets with relative ease. But there is not a unified data format or metadata structure that allows GML to offer an overarching data archive interface from which users can drill down to the

specific data they would like to have. There is also not a central, master web location where data availability for different parameters at different sites through time can be visualized. Latency in making data usable for the general community is high in many cases. While there is an appreciation that quality takes time, taking advantage of software engineering and data management expertise to implement structures that are automated where possible and make human interaction in the process expedient and routine, will help with latency issues.

**Accessible:** variably moderate. GML should consider uniformly adopting NetCDF to align with the general research community. This is a crucial first step in developing machine-readable metadata that forms the foundation of data accessibility. Until we all make the effort in this transformation and agree upon metadata standards, barriers to integrating large datasets addressing complex science questions will persist. There are active groups within the community working on this problem, and NOAA is often underrepresented in these efforts. While ASCII data formats can seem simple, in today's world of automated data processing, separating information such as locational, quality, and calibration information can require extra steps for those using the data for analysis or satellite or model validation.

**Interoperable:** variably moderate. The efforts that OBOP is making to standardize very basic technical elements such as cabling and data loggers are the foundation for building an interoperable data archive. OBOP is commended for these proactive measures that benefit the research groups. However, each group's measurements have been managed separately for decades as its own program, so it is difficult to get to a truly interoperable place. There are some areas where data products are produced with model integration in mind, and in doing so, are interoperable in a limited way (ObsPack). Some of the radiation data is developed for satellite retrieval evaluation by NESDIS. But in general, data products available to the general public have not been approached with interoperability and use cases in mind to guide formats, metadata, and delivery methods.

**Reusable:** moderate to low

Once published, GML data can be found on the archive through time. However, most data sets do not have Digital Object Identifiers (DOIs). This is an essential tool in today's research world to ensure identification of the exact dataset used for any purpose.

## **2.4 Performance enhancement avenues to help GML better address strategies related to GHGMMIS**

The U.S. Global Change Research Program (USGCRP) was established by Congress in 1990 to coordinate and facilitate collaborations and cooperation across 15 federal member departments and agencies, including the Department of Commerce (NOAA and NIST). The Program's stated mission is to empower the Nation and the world "to anticipate and respond to urgent risks of climate and global change by creating and

providing accessible, usable knowledge.” Since inception, the USGCRP’s climate change efforts have focused on how to adapt to the unavoidable impacts of climate change. This creates requirements for NOAA and partners for observations and modeling efforts that characterize and forecast climate change impacts and deliver the knowledge needed to adapt to impacts on human and natural systems and increase resilience. In response, the Department of Commerce has presented NOAA as the ‘Climate Agency’ for delivering adaptation ‘Climate Services’ for how to reduce vulnerability and increase resilience to unavoidable climate change impacts on human and natural systems.

GML has been the central institution globally for CO<sub>2</sub> and CH<sub>4</sub> observations for over 5 decades. Because of this, every other observation program intentionally ties itself to the GML-centered observation program. This makes sense given the small variations in the concentrations of these molecules. But given the increased attention on the measurement of these two molecules, GML should consider changing their strategy to better account for both the increased number and types of observations occurring now and coming on-line in the next 5 years as well as the increased number of flux retrievals and information systems that are now in development. This includes better integrating their focus on in situ observations with the various kinds of satellite data now being produced and expected to increase substantially in the near future.

Effective mitigation of greenhouse gas (GHG) emissions relies on emission estimates with sufficient accuracy and precision that are mapped with sufficient granularity in space and in time. During the review, GML presented results of work led by Lei Hu and Steve Montzka in partnership with inventory compilers in EPA, who are responsible for preparing the annual US GHG National Inventory Report (NIR) to the UNFCCC. This project demonstrated the added value of combining emission estimates from sector-based activity data and emission factors prepared by EPA inventory compilers, and emission estimates derived from inverse model analysis of atmospheric GHG concentration gradients determined by the NOAA network of tower and airborne flask measurements.

This pioneering proof of concept showed that adding the atmospheric-measurement layer of information (hybrid “top-down plus bottom-up”) led to improved a posteriori emission estimates and newly found mitigation opportunities. It also resulted in the official inclusion of these hybrid results in the EPA’s NIR and was an inspiration for the launch of the U.S. GHGMMIS. In addition, it led NOAA to establish the US Emission Tracker for Potent GHGs Tracking emissions over the contiguous US. However, there was no GML budget to cover the needed inverse model analyses, the timely QA/QC of the F-Gas flask measurements, or staff time for necessary periodic communication/meetings with EPA inventory compilers for the hybrid analyses. Instead, this pioneering work was funded through a philanthropic grant made to UC Boulder CIRES. This successful NOAA EPA collaboration is a quintessential example of translating scientific research to climate services for mitigation, and was a foundational motivation for the creation of GHGMMIS. The recommendations include guidance related to the above challenges and opportunities.

Of course, this could all change with the upcoming change in administration. If it does, then reassessing GML's strategic stance on this topic is called for.

## **2.5. GML's efforts to improve workforce diversity and inclusion.**

This report and recommendation are based on the DEIA presentation and discussion from Wednesday morning, GML Director's overview presentation, and stakeholder reports. The DEI activities presented to the panel outlined efforts to create an atmosphere of inclusion and psychological safety, as well as a training program aimed at preventing staff from becoming silent bystanders and encouraging awareness of their surroundings. Three goals stand out as commendable from the perspective of inclusion within GML. The presentation and exercise partly address NOAA's core value of inclusion: "We embody a culture of equity that embraces diversity, differing abilities and fair and respectful treatment" while also fostering employee cohesion. There is also a plan to build a stronger partnership with diverse communities across the nation. However, based on the presentation given to the review committee, it is not possible to adequately answer review question five (5) above.

**Quality:** The question above suggests that NOAA GML has improved the diversity of its workforce. However, this was not evident from the presentation. The demographics of the existing staff presented did not reflect a workforce that is "more representative of the U.S. workforce population" as the question seems to suggest, by any measure.

**Relevance:** GML is a relevant and highly capable national treasure. Its measurements are especially important to underserved communities and their health. Equitable treatment of staff is a core NOAA value, and GML's report addresses many of these points and guidelines.

**Performance:** It is hard to judge the effectiveness and efficiency of how GML recruits and diversifies its workforce. It is not clear where and how the available positions are advertised to recruit new employees. The review committee did not find any plans outlining how the recruitment of new laboratory members will be pursued. There was no discussion of such efforts in the documents shared with the review committee. As a result, it is not possible to provide a performance metric for the topic of workforce recruitment and diversity.

**Overall DEI summary:** GML's report did not adequately address this review question. While the numbers on gender parity are not outliers, the lack of reporting on efforts made to date and the absence of connections to other NOAA initiatives (such as the NOAA Experiential Research and Training Opportunities, NERTO) led the review committee to conclude that GML still needs to develop actionable strategies to ensure the Laboratory maintains not only a talented but also a diverse workforce. This finding requires the highest level of attention from senior leadership as the future sustainability and resilience of GML's activities are at stake.

## **3. Findings and Recommendations for the Three Scientific Themes**

Important capabilities are detailed here along with guidance to enhance performance.

### **3.1 Theme: Tracking Greenhouse Gases and Understanding the Carbon Cycle**

This is probably the most prominent area within GML and certainly one that gets the most attention both domestically and internationally. As stated earlier with respect to the GHGMMIS question, GML's observation program is the backbone of the international observing system for CO<sub>2</sub> and CH<sub>4</sub>. And these observations are fundamental in understanding the Carbon Cycle. However, they are only part of the carbon cycle as carbon comes in many forms. It's difficult to understand the Carbon Cycle with JUST the observations of the atmospheric forms of carbon. The research of the carbon cycle at GML rarely includes looking at the other relevant observations. Plus, satellite data for CO<sub>2</sub> and CH<sub>4</sub> are only going to grow over the next 5 years. It should be an imperative to better integrate the work at GML with those missions. Some of that has occurred with OCO-2, but the progress has been slow and not always helpful.

GML has a clear and sustained record for producing *quality* data and analyses that have advanced understanding of GHG trends and carbon cycle feedbacks. Their work is highly relevant both to the global research community and also to address policy, as evidenced through use by other US government agencies such as the EPA. One area that should receive attention in the future is the promotion of activities that will improve understanding of transport and distribution processes. Other parts of GML (Theme 2) and NOAA (ARL, GSL) have a strong interest in, and measurements for, boundary layer processes so partnerships could help to move this effort forward. Another gap that emerges as work at traditional scales (mid- to -large-scale) matures, is study of small-scale processes and their relationship to those larger-scales. Knowledge could be gained by developing observational systems (that might move across regimes) or collaboration with other groups doing this work, as there are many (e.g., NSF NEON, DOE).

An important decision point under Theme 1 is to determine the level of resources that will be committed to modeling efforts. An in-house modeling program has clear benefits in sustaining quality measurements and their interoperability for various applications. However, GML must be discriminating in how and how much it will build modeling as a support to its primary goals of monitoring and analysis. The lab should have a strong understanding of their goals for modeling – to develop new observations or sampling strategies? to interpret observations? – what it really needs to do for itself, and where it can partner. GML is already using OSSEs to guide needs, which is commended. But general model improvement will also improve the outcomes of OSSEs. So if a larger modeling program is to grow out of GML, it is something that should be considered by OAR for additional support. A recommendation on this topic: leadership can work with other NOAA labs to develop mechanisms for cross-lab collaborations for bringing models and observations together. This will reduce the burden on GML for developing a large program and leverage existing NOAA investments. These mechanisms need to incentivize use and make clear that all partners are equal in bringing strengths to the table in observations, modeling, and interpretation in order to be successful and sustained.

### **3.2 Theme: Monitoring & Understanding Changes in Surface Radiation, Clouds and Aerosol Distributions**

This scientific theme is highly important for the climate system and highly relevant to meeting the NOAA objectives. This theme relies heavily on existing types of observations developed elsewhere and deploys them at NOAA and NOAA-affiliated locations. Because of the nature of these types of observations, developing new observational techniques does not make sense as these observations need to be integrated with other observations being made internationally to better understand the global budget. Because of the highly variable nature of these types of observations, there are never sufficient observations to truly get the coverage needed to answer key science questions. The only way to do that is to tie in the observations with those of satellites. It was difficult to understand from this review how much of that really occurs with this theme's team. The panel would encourage this team to be more integrated with the various long term satellite products related to clouds and aerosols to maximize the scientific output of this activity.

The radiation group is known for its high data quality and it is clear that the group has grown in its research strength and breadth of topics it is addressing since the last review. The merging of the radiation and aerosol groups will improve its relevance if it can truly integrate measurements to address new topics such as radiative forcing and aerosol-cloud processes. Impacts of the aerosol theme are more through providing data for model evaluation and less through research on basic physical process understanding. The radiation side has an ability to do both with senior staff that have led GML in this space for many years and new, talented junior staff. The work presented on linking Dimming & Brightening to global modes of variability is excellent and important work and an elevation of the sometimes more technical research papers produced by the group. It has strong relevance to understanding global scale temperature and pressure patterns and shifts in circulation and how these patterns impact regional to local-scale cloud and surface radiation budget conditions over decadal timescales. These are important outcomes for improving both understanding and prediction, NOAA's primary objective.

The level of internal to NOAA (GSL, ARL, CSL, PSL for observations and analysis) and external (DOE, international organizations through grants and field campaigns) collaboration is evident, allowing this group to have an outsized impact. The collaboration with GSL is essential to identify weather model biases and drivers and has grown. Also, there is a stronger focus on emerging relevant applications such as renewable energy and wildfire that are societally relevant. Improvements in these areas will certainly positively impact GML relevance if they are sustained.

Potential areas of focus for the future are in capitalizing on recent effort in measuring boundary layer properties and collaborations with labs such as GSL that model and advance understanding of processes in the PBL. Coupling this with SURFRAD in the US and BSRN globally, there is the opportunity to put together pieces to define the regimes and regions where processes are more or less globally, regionally, or locally driven and how that benefits predictability. GML should focus on how they might package information to feed into operational activities such as NWP. Data products that are aggregations of multiple direct measurements or higher-level retrievals or even indices may serve this purpose well.

Two areas where the new merged aerosol and radiation group might find a niche where other agencies are either not set up to focus or have declined to prioritize are:

- Defining the relationship between in situ and remote sensing aerosol measurements and hygroscopicity. This relationship is critical for using the broad spatial coverage of in situ aerosol properties to improve our understanding of aerosol radiative forcing. It could require reshuffling of measurements to get in situ aerosol measurements, water vapor, MFRS Rs, etc. collocated in key aerosol and humidification regimes, but if done routinely in a couple of places there could be a substantial payoff.
- Spectra for aerosol and cloud retrievals. There is information content there and other agencies have largely declined to pursue the space.

### **3.3 Theme: Guiding the Recovery of Stratospheric Ozone**

This scientific theme has been busy over the past 5 years! The ODS observation program has been integral in assessing the short and long-term changes in various ODSs and related gases using both GML observations and those from the AGAGE network. These two networks use somewhat different observational techniques and maintain/propagate their own gas standards. Their cooperation/collaboration has been key to addressing many concerns from the parties to the Montreal Protocol. The GML Senior Scientist has become a Science Assessment Panel spokesperson for communicating the analysis of these data to the Parties. The need for such communication will continue to grow in the near future. The need for additional observations, some of which may be funded by the Montreal Protocol itself, will also continue to grow. Because the techniques used by NOAA are less costly than that of AGAGE, much of that potential growth will occur in flask sampling. It is not clear that NOAA has the person-power to keep up with these coming demands.

Ozone sondes and surface ozone column observations are also an important area, and concern, for NOAA GML. Many of the international organizations funding those types of activities are scaling back their investment, making the observations from GML all the more important. Sondes in particular are one of the few types of observations that can regularly obtain ozone profiles throughout the troposphere. The other is tropospheric ozone lidars, which are expensive to operate. Satellites have a difficult time assessing profile information of ozone in the troposphere. They NEED sondes to assess the retrievals, and fewer of them now exist. This is an area of growing concern.

As with Theme 2, this theme has expanded its reach through partnering, leveraging the GHG network to expand. Kudos for leveraging existing GML infrastructure to expand the lab's capabilities and impact. The expansion of the surface ozone network is also producing exciting new science.

In addition to consistent monitoring and network expansion, rapid response deployments are helping to track change in ozone and also point to specific processes that are drivers of these changes. GML does not have a strong legacy in studying dynamics and so should continue this work – to better understand how processes such

as volcanic eruptions, aerosol distribution, and general transport patterns impact ozone – but in partnership with groups with strong expertise. Another fruitful collaboration with CSL has enabled substantial expansion of water vapor balloon sampling to add POPS measurements for stratospheric aerosol sampling.

Finally, as the U.S. struggles with supporting continuous and comprehensive space-borne measurements, it is even more critical for GML to maintain and expand sampling to provide this critical information for informing compliance of international policy and climate prediction. These data are absolutely critical in international assessments and reports, which will only grow due to absence in satellite data.

The tracking of ODSs has been exceptional. The identification of the CFC-11 emissions increase was first-rate policy-relevant science, and the Parties to the Montreal Protocol are now in the process of increasing the observational coverage to improve regional emission estimates. Of course, the application of standards to these observations is key to accuracy and precision estimates that make global emission observations credible. These unassailable standards and observations ensure the seriousness and credibility with which policy makers view the GML data. The lab work on ODSs (as with all of these halogenated species) is high quality state-of-the-art science. The ability to diagnose trends in human-produced emissions is tied to both the quality and to the long-term sustainment of the observations. These trends and changes are key facts for policy makers – fulfilling a principal role for NOAA.

## **4.0 Recommendations**

### **4.1 Overarching recommendations**

1. **Grow:** Do not shrink GML. This requires funding increases in every area, not necessarily huge, but *solid and sustained*. Federal hires, 10-12 of them divided evenly between senior management/group leaders and more junior scientists, need to occur as soon as possible.
2. **Expand:** The science conducted by GML must expand to meet the demands for climate-related data across all these areas and to enable partnerships that transfer knowledge for even greater benefit to the Nation and beyond. OAR's priorities must shift to ensure that GML can expand its measurements of chemical species across broader geographical regions. NOAA's budgets and personnel must continue to support a range of activities stemming from national and international commitments to data collection, calibration, scientific reviews, and the assessment process.
3. **Funding:** Budget and hiring plans must support their work, and both need to expand to enable GML to better fulfill its mission. Funding from NOAA must be increased in all areas. Atmospheric baseline observatories must be maintained as there is no redundancy. The decline in the number of federal personnel, particularly senior staff, must be reversed. Succession planning to attract experienced leaders and put promising junior scientists on a career track must begin as soon as possible.

4. **Visibility:** NOAA and GML both need to make GML's work and its scientists more visible. Actions could include: (1) more publications postings, press releases, and updated personnel websites; (2) NOAA awards and promoting recognition by professional societies such as the American Geophysical Union, American Meteorological Society, and American Association for the Advancement of Science.
5. **Collaboration:** Collaborative opportunities for all of GML's groups should be better exploited within GML, across NOAA, and with external organizations. The impact and reach into policy can be further boosted by collaborating with modeling groups at NOAA labs, NASA, NSF, and Universities. The collaboration work that has started in the boundary layer modeling and analysis with GSL should be strengthened and expanded to other areas, such as flux inversions, as well. Coordination and cooperation with existing networks should be a high priority with GML. NOAA GML should try and take a leading role with the WMO G3W, while doing significant cooperation with AGAGE.
6. **Strategic Planning:** Together with GML senior leadership, GHG/CC needs to develop a strategic plan that defines goals for the next 5 and 10 years, along with appropriate implementation strategies. The plan should also include better integration of measurements and models within the themes, and with NOAA's climate model Labs and beyond.
7. **Leadership:** Refresh GHG/CC leadership at all levels. There needs to be clear career paths and timetables for promotion of federal staff, and for hiring promising CIRES scientists to federal appointments. The group should focus on writing fewer external proposals.
8. **Modeling:** GML should plan on an optimum observation-modeling mix. GML should nurture/expand their communication with the other NOAA labs to achieve this mix (see Collaboration above). The modeling should mainly be to help GML "operationalize" the observations, which are critical for national and international. Modeling (e.g., Carbon Tracker) and analysis should be well supported to ensure full utilization of observations. The modeling activities allow harvesting of key policy-relevant information from the various arrays of observations.
9. **Staffing:** The high-caliber calibration, standardization, and maintenance of the state-of-the-art laboratory are being managed by one or two senior scientists. GML and NOAA leadership should implement a transition plan well ahead of eventual retirements to allow sufficient time for trust-building and mentorship of young scientists. Furthermore, for many of the GML activities, the number of scientists managing them is quite limited. NOAA OAR and GML leadership should be cautious not to overburden the existing staff as this could impact data collection.
10. **Overburdening:** GML operational levels appear to be overburdening staff. It is critical to not overwhelm staff with laboratory analysis and the production of standards. GML management should quantify staffing levels to ensure they can

meet observation requirements and provide necessary scientific analysis. While long work hours and weekend work regularly are common for career-advancing scientists, management needs to monitor and adjust staffing levels to prevent overburdening.

11. **DEI:** The panel recognizes that expanding the workforce diversity is extremely challenging for an organization located in an environment with a high cost of living. We appreciate the adoption of the NCAR model for making GML a psychologically safe place for everyone. There are several specific avenues to increasing workforce diversity that are enumerated below.

## **4.2 Specific recommendations**

### **1. Monitoring & Understanding Changes in Surface Radiation, Clouds and Aerosol Distributions Recommendations:**

- a. Commit resources to fill out instrumentation at existing networks, e.g. add SURFRAD type instruments to existing UV, aerosol and latent/sensible heat flux sites and vice versa, to provide denser sampling of US climate zones.
- b. Expand measurements at existing sites, e.g., install ceilometers and cloud optical depth spectrometers.
- c. More closely integrate the aerosol group science within GRAD . If possible, combine the two groups to achieve closer to critical mass.
- d. Expand products useful for the renewables market.

### **2. Guiding the Recovery of Stratospheric Ozone Recommendations:**

- a. The network of total ozone ground observations should be maintained to both validate satellites across latitudes and seasons, but also to ensure the credibility of ozone and water vapor variability and trend estimates. Provide sufficient resources to keep ODS data-collection techniques current.
- b. Sonde observations are critical to both ground-based trend and variability estimates but also key to satellite validation. The network of sondes and total ozone ground observations should be maintained to both validate satellites across latitudes and seasons, but also to ensure the credibility of ozone and water vapor variability and trend estimates.
- c. While some useful work on ozone and water technology was evident, GML should develop and coordinate a long-term plan to sustain and improve the ozone and water vapor profile and ozone column observations for the future.
- d. Implement a succession plan for group leadership and consider combining the LOGOS and OZWV groups.

### **3. Tracking Greenhouse Gases and Understanding the Carbon Cycle Recommendations:**

- a. Modeling (e.g., Carbon Tracker) and analysis should be well supported to ensure full utilization of observations. The modeling activities allow harvesting of key policy-relevant information from the various arrays of observations. The models provide key connections from observations to policy, and should be supported as part of GMLs overall mission.
- b. GML should consider the sampling of HFCs at some of the long-term Greenhouse Gas Reference Network stations outside of North America. On a global scale, HFC emissions derived from the analyses of measured atmospheric concentrations are significantly higher than the emissions reported to the UNFCCC by Annex I countries. There is a large and growing gap between reported HFC emissions and measured emissions, with about 60% of current emissions going unaccounted. The dramatic increase in this emission gap over time is consistent with substantial growth in HFC production, use, and emissions in non-Annex I countries that are not obligated to report emissions to the UNFCCC. Unfortunately, in the absence of controls, about 85% (~60 gigatons) of HFC emissions between now and 2050 are expected to occur in these developing countries where there is currently no monitoring of regional emissions by atmospheric monitoring. This massive blind spot means we cannot even begin to know if countries are on track to meet the emissions reductions expected from their commitments to reduce production and use that they made by ratifying the Kigali Amendment to the Montreal Protocol. If collection systems at some GGGRN stations (close enough to source regions) were to be optimized for the measurement for HFCs (with addition of flask packages to increase from weekly to daily sampling), it could be a very cost effective way to greatly enhance the visibility and transparency of HFC emissions around the world, which is critically needed for managing these powerful climate forcers.
- c. Maintain the US Emission Tracker for Potent GHGs Tracking emissions over the contiguous U.S..
- d. Support the timely QA/QC on the F-Gas measurements, as well as ongoing inverse model analyses.
- e. Additional support is needed for staffing/labor the periodic meetings with EPA inventory compilers for joint analyses and comparisons of the activity data/emission factor information with the regional distributions and temporal variations in the emission estimates from the inverse modeling of atmospheric concentration gradients.

4. **Standards** and laboratory analysis should be well funded and staffed to ensure the continued outstanding data quality for GML's state-of-the-art observations.
5. **Balanced expansion:** GML needs a careful balance between new measurements against boosting continuity and depth of critical long-term data observations. A careful balance of expansion while making sure of the stability and resilience of existing long-term observations should be made. When possible, expansion through collaboration with existing networks at NOAA and/or international (e.g. AGAGE, Global Greenhouse Gas Watch, GRUAN, etc).
6. **Innovation:** GML needs to be innovative in its communication and automation along with the development of new techniques and measuring systems (as was evident in the theme presentations). Research on better automation, simplification, and cost reduction should be a high priority. There also needs to be an emphasis on training young scientists and students in the operation of these new systems.
  - a. The measurements with both GC-MSs and flasks should be expanded to improve regional quantification of emissions for multiple species across the globe. This expansion should be achieved in coordination with other observational networks and international organizations. Enhanced observations would enable better information and support for US policy makers.
  - b. The flasks collected at the very large number of sites are currently only analyzed for CO<sub>2</sub> and CH<sub>4</sub>. These could be analyzed for F-Gases leading to a denser network of F-Gas measurements and provide data needed for more coverage and granularity for inverse model footprints and the resulting emission estimates. This would help attribute the 60% (and rising) of global HFC emissions currently unattributed to regions and countries of origin.

## 7. DEI Recommendations

- a. DEIA and reporting of conflicts. The lack of an independent "ombuds person". During the review committee's visit, the absence of an independent "ombuds person" was raised several times in our discussions. This issue was highlighted, particularly given that reporting currently goes directly to leadership, which has an admirably open-door policy. However, NOAA and GML should establish, or make easily accessible (if a NOAA OAR office already exists), a mechanism for independent reporting of concerns to address potential biases.
- b. GML should grow and expand through partnerships. Innovation and strong collaboration with other NOAA laboratories and NOAA CSCs, through NOAA EPP, could serve as avenues to change the organizational culture and improve workforce diversity. GML should actively engage with, expand, and potentially become involved in the NOAA EPP NERTO

program to attract and mentor graduate students, who could one day become GML employees. GML leadership should also consider developing regional partnerships with Historically Black Colleges and Universities (HBCUs) to engage faculty and students in the collection of samples at GML stations across the nation. These details are raised because the demographic chart included in the GML Director's presentation did not mention African Americans (although a 100% diversity is reported for the staff involved in the administration of the Laboratory).

- c. GML leadership should frequently emphasize the importance of workforce diversity in relation to the sustainability of GML's activities. Leadership must foster a culture within GML that prioritizes recruiting laboratory members from diverse backgrounds, in alignment with both NOAA OAR's vision and core values, as well as the strategies outlined by the National Science Board (<https://www.nsf.gov/nsb/publications/2020/nsb202015.pdf>). The review committee did not find credible the justification that staff diversity is limited by the population of Boulder. As a national treasure, GML has both global and national reach. Therefore, it is imperative to engage diverse populations as sources of science exchange and to consider appointing a "compensated" equity and inclusion champion to lead these engagement efforts. GML has sites distributed around the globe and reports geographic distributions of its workforce, even in Alaska (4.7%), for example. Innovative ways of involving local residents would not only be good business practice but would also contribute to workforce diversity.

## **8. Data recommendations**

- a. Data management at GML has not received the attention and resources needed to keep up with the fast-moving management and archival advances. It is understood that data management and delivery are large and costly enterprises. With limited resources, prioritizing data delivery may not seem viable within GML, so potentially leveraging capabilities in other parts of NOAA should be considered. In terms of leveraging internal capabilities, the aerosol group is likely the most advanced in this area with the development of their FORGE software. The emerging use of this software by radiation groups is a good start. At a minimum, GML could benefit from consulting with managers of large archives to gain insights into how to structure and maintain a modernized archive. Given their uniformity through time, some data management functions should be relatively simple to structure and automate. We are already in the time of cloud services and computing, with on-prem data access and computation becoming less central. If GML invests significant resources into building a local, unique system while the rest of the world goes with more centralized solutions, it could hamper cross-collaboration within NOAA and the development of a broader user base, both nationally and internationally.

- Modernization of the GML data delivery framework to meet FAIR principles. Look to other parts of NOAA (NCEI) that might be able to take on some of the mechanistic aspects of data management, leaving the process and quality assessment to GML scientists and ask OAR to support this effort.
  - Provide uniform data formats (NetCDF) and metadata for reported variables to improve access to data for integrative research topics and higher scientific impact.
  - Build reportable data use metrics for the range of data that GML produces to help with prioritization of resources.
  - Mint all data sets with a DOI.
  - Remove barriers such as requiring passwords for data access.
  - Improve data latency through development of standard processes, timelines, and automation where possible.
  - Data plots on the web provide a zeroth order check on data files, but these data plots need to be routinely updated and timely.
  - The documentation of analysis products and tools needs to be enhanced. E.g., CarbonTracker.
- b. Meta-data and data-archiving work should continue. In addition, GML should seriously think of improving data latency of the in-house data but also encourage, when possible, other partners (GAW stations etc.) for a quicker delivery and dissemination. GML needs to scale-up the impact of their data while rewarding Diamond data that is not seen on time loses its impact in policy and is a loss for GML as well.
- c. GML should make a greater effort to lead global observation networks.
- Make SURFRAD into a central location for other surface observations (perhaps with a better interface to US Climate Reference Network, SOLRAD, and the DOE ARM).
  - Interfacing with the AGAGE network would link the mutual data sets, and provide coverage for gaps in the respective networks.
  - NFAN aerosol data should be consistent and submitted to the World Data Center for Aerosols (WDCA) – EBAS archives so these data are available to the international community.