Summary Report of the Review of the Geophysical Fluid Dynamics Laboratory

29-31 October 2019

Review Panel

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1. Overview

The Science Review of the Geophysical Fluid Dynamics Laboratory (GFDL or "the Lab") was held on site and at Princeton University on 29-31 October 2019. The Review Panel (hereafter, "the Panel") assessed three research themes of GFDL activities for the period 2014-2019: Theme 1 (*Modeling the Earth System*), Theme 2 (*Understanding Earth System Phenomena*), and Theme 3 (*Earth System Predictions and Projection*). The Panel was charged by NOAA Research leadership with addressing the quality, relevance, and performance of each theme and asked to provide recommendations as needed.

In preparation of the review, two conference calls between NOAA personnel and panel members were setup on 6 September 2019 and 22 October 2019. Led by NOAA's Office of Oceanic and Atmospheric Research (OAR) Headquarter Coordinator, these calls provided review instructions, logistical details of the visit, and information about resources relevant to GFDL and its relationship to NOAA OAR's strategic plan, mission, and priorities.

Each panel member was instructed to prepare independent written evaluations in the provided template. The charge to the panelists was to provide an overall rating of "Highest Performance," "Exceeds Expectations," "Satisfactory," or "Needs Improvement" as well as ratings for the quality, relevance, and performance on each Theme. Guidance to each of the above-mentioned categories was also provided. The reviewers were asked to identify specific areas of improvement. Feedback on the review process was also solicited from the Panel with a goal to improve the process for future reviews.

The Panel Chair was tasked with summarizing the individual evaluations, developing a list of actionable recommendations, and compiling them into a summary report. As per the guidance provided, NOAA leadership was not seeking a consensus report. The individual evaluation forms were also provided verbatim to OAR leadership.

Section 2 provides the individual ratings of panel members. Each panel member has been randomly assigned a reviewer number. Section 3 combines the remarks and observations of the panel members for each research theme, with specific recommendations. Section 4 synthesizes these observations into key emerging areas that are applicable across the Lab. These areas then form the basis for actionable recommendations provided in Section 5. Finally, remarks about the review process are given in Section 6. These remarks also include comments addressed directly to NOAA OAR.

2. Summary of Individual Ratings

The table below summarizes the assessment ratings of each panel member for Theme 1 (*Modeling the Earth System*), Theme 2 (*Understanding Earth System Phenomena*), and Theme 3 (*Earth System Predictions and Projection*). For brevity, "Highest Performance" rating is denoted in the table as HP, "Exceeds Expectations" as EE, "Satisfactory" as S, and "Needs Improvement" as NI. Themes for which a panel member did not provide an evaluation are left blank.

Summary of the 2019 GFDL Review

	Reviewer 1	Reviewer 2	Reviewer 3	Reviewer 4	Reviewer 5	Reviewer 6	Reviewer 7	Reviewer 8	Reviewer 9
Modeling the Earth System	**HP**	**HP**	**HP**	**HP/EE**	**HP/EE**	**HP/EE**		**HP/S/EE**	**HP**
Quality	HP	HP	HP	HP	HP	HP		HP	HP
Relevance	HP	HP	HP	HP	HP	HP		S	HP
Performance	HP	HP	HP	EE	EE	EE		EE	HP
Understanding Earth System Phenomena	**HP/EE**	**EE/HP**	**HP**	**HP/EE**	**EE/HP**	**EE**	**HP/EE**	**EE/NI**	
Quality	EE	HP	HP	HP	HP	EE	HP	EE	
Relevance	HP	EE	HP	HP	EE	EE	EE	NI	
Performance	HP	EE	HP	EE	EE	EE	HP	EE	
Earth System Predictions & Projection		**HP**	**EE/HP**	**EE/HP**	**EE/HP**	**HP**	**HP/EE**	**HP**	**HP**
Quality		HP	EE	EE	HP	HP	HP	HP	HP
Relevance		HP	HP	HP	EE	HP	HP	HP	HP
Performance		EE	EE	EE	EE	HP	EE	HP	HP

Thus, the ratings for each theme are as below:

Theme 1: HP, HP, HP, HP, HP/EE, HP/EE, HP/EE, HP/S/EE

Theme 2: HP, HP/EE, HP/EE, HP/EE, EE/HP, EE/HP, EE, EE/NI

Theme 3: HP, HP, HP, HP, HP/EE, EE/HP, EE/HP, EE/HP

3. Findings and Recommendations by Research Themes

(a) Theme 1: *Modeling the Earth System*

Quality of Theme 1: Panel members generally concluded that GFDL has produced world-class models for studying the Earth System. Building upon its reputation and proven track record, the Lab has made great strides in developing its next-generation models with the inclusion of atmospheric chemistry and a new land model. Specific examples demonstrating the high-qualify of GFDL models are DYAMOND (DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains) that resolves clouds globally and the high-resolution MOM6 (Modular Ocean Model) that simulates oceanic eddies.

Summary of the 2019 GFDL Review

Model development efforts are converging on a set of nearly unified configurations in which interchangeable model components (of different grid resolution and types) can be used to address subseasonal prediction to long-term climate projections. These efforts support GFDL's vision to increase the Lab's modeling capabilities to help address issues related to ecology, fisheries, and biogeochemical cycling. Advancements in model development have led to better simulations (e.g., of the Madden-Julian Oscillation or MJO) and the reduction of long-standing biases in climate modeling such as those related to the top-of-the-atmosphere (TOA) radiation and the double Inter Tropical Convergence Zone (ITCZ) problem. Reviewer 6 summed up that "GFDL has made impressive progress in modeling the Earth System in the past five years. The team excels in their traditional strengths in atmosphere and ocean modeling."

Specifically, the development of GFDL's Finite-Volume Cubed-Sphere Dynamical Core (FV3) component is of very high quality, especially for the cloud-resolving regime. It should enable simulations and forecast across a wide range of scales with nested or stretched grid and will be a pillar of advancements in the other GFDL research themes.

Reviewer 4 complimented the GFDL's modeling effort and noted that "the 'recent' expansion into Earth System modeling has been with some resounding success." Reviewer 8 felt that "GDFL's uniqueness is the strength in the modeling activity." "By many metrics, CM4 performance is at the top of the CMIP5-class models, and it is likely one of the top models of the world in CMIP6 generation," remarked Reviewer 9. Reviewer 6 further added that significant advances in GFDL Earth System modeling are evident by "new features in the land model such as modeling vegetation dynamics using the perfect plasticity approximation (PPA), development of the Hydro-blocks model to capture land surface heterogeneity, and modeling of N [nitrogen] cycling, including riverine N processes."

Overall, the strong modeling products have positioned GFDL to conduct preeminent research that supports the understanding of the Earth System and its predictions/projections. Reviewer 3 acknowledged "GFDL's remarkable progress in model development. The Lab continues focusing on diverse lines of model development. This is evident from the wide variety of accomplishments in developing high-quality parameterizations and software infrastructure for components of the Earth System model."

Relevance of Theme 1: The Panel noted that GFDL's efforts in modeling the Earth System and resulting products to be particularly relevant to NOAA, to other governmental agencies, and to the scientific community at-large.

During the past five years, GFDL has developed and contributed tools that support NOAA National Weather Service (NWS). GFDL FV3 dynamical core was selected for operational use by NWS. Components such as MOM6 as well as FV3 have been widely adopted by other U.S. climate modeling centers and legacy atmospheric component continues to be highly favored in the academic community. GFDL-developed cloud microphysics has been adopted in the NCEP fvGFS operational weather forecast at EMC. Conversely, GFDL has adopted model components of other centers such as the DOE-led CICE consortium.

Summary of the 2019 GFDL Review

Reviewer 1 noted that "GFDL is the 'go-to lab in NOAA' for modeling needs the NWS may have." Reviewer 2 remarked "that some variant of SPEAR may underlie the next generation of NCEP's climate forecast system, given its much-reduced systematic biases and excellent ENSO simulation." Reviewer 4 found "the work performed at GFDL transcends the laboratory and traditional boundaries of climate modeling."

Given GFDL's collective expertise, stakeholders with whom the panelists had an opportunity to interact mentioned the high-level model efforts should continue to be relevant. Legacy GFDL models (like HiRAM, FLOR, HiFLOR) have high scientific reputations worldwide. Variants of GFDL atmospheric models are preferred in the academic community that needs a fast and computationally efficient global climate model to explore climate dynamics. The shift toward open development of MOM6 is encouraging as it helps transition the broader GFDL efforts toward true community involvement.

The Panel observed that GFDL has taken initiatives in maintaining its relevance in this theme. Though not provided additional funding to do this, GFDL contributes to the operational NMME seasonal forecast ensemble with a state-of-the art model configuration. GFDL also provides high-quality model results to the CMIP6 archive as well as the IPCC Sixth Assessment Report. These activities point to GFDL's dedication to service and further substantiate GFDL relevance with respect to other CMIP models.

Performance of Theme 1: Over the last five years, GFDL has clearly expanded its scope to incorporate atmospheric chemistry and biogeochemistry. In supporting this expansion, GFDL has adopted a balanced approach to model development and fostered close interactions between group leaders of various model components. As Reviewer 2 noted, GFDL is "very cost-effective relative to its overall budget and HPC resources while remaining as best-in-class among NOAA labs." GFDL scientists have clearly demonstrated leadership at national and international venues with respect to modeling efforts as evidenced by participation in studies, conferences, and other appropriate venues. The list of awards and honors for the past 5-year period is impressive. Examples are GFDL's involvement in the IPCC Sixth Assessment Report and contribution to inter-model comparisons via CMIP6.

GFDL has developed model configurations and components that are being adopted by NOAA operation as well as various stakeholders. In commending the Lab's strong leadership in developing state-of-the-art Earth System models, Reviewer 3 remarked that GFDL scientists "demonstrated how they go beyond the established expertise of theirs by addressing new scientific challenges related to interactive coupling of climate-relevant biogeochemical cycles, including riverine fluxes from land into coastal ocean. Thereby they endeavor to apply Earth System models not only for climate-relevant science, but also for addressing societally relevant questions related to (for instance) marine resource management."

However, in expanding its scope, some efforts in modeling (like the stratosphere and land-ice) are subcritical, i.e. carried out by few individuals. As Reviewer 5 remarked, the Lab may need "to increase efficiency through leverage partnerships, other than with Princeton University through CIMES." Similarly, awareness of relevant developments occurring outside of GFDL was not clearly evident. In addressing model complexities inherent in the Earth System, this insular approach which may have worked well in the past might hinder GFDL in the future. Reviewer 1 further echoed this concern about

GFDL scientists "being over-extended, resulting in them not being able to reach out sufficiently to others in the community who are undertaking research on similar topics."

The Panel viewed the performance evaluation of GFDL Earth System model as an on-going process. Reviewer 2 stated that "AM4/CM4 simulation of present-day climatology is documented to be more skillful overall than all the CMIP5 models." Formal comparison efforts with other CMIP6 models within the U.S. and with other modeling groups are just beginning. GFDL views its participation in CMIP as a contribution to a globally coordinated effort in defining consensus estimates and change. Early indications are that GFDL models will be ranked among the top in terms of climatological estimates, particularly those related to clouds and radiation.

Recommendations for Theme 1: Over the past five years, GFDL has made great strides in contributing to NOAA operations and Earth System modeling. Going forward, care must be exercised to ensure GFDL's preeminence in research and its core strength in climate physics. The recommendations below aim to help the Lab overcome foreseeable challenges related to the Lab being short-handed in staffing, being isolated, being mired in the Earth System complexity, and improving model development.

The Panel encourages GFDL to find ways to overcome subcritical efforts. Reviewer 5 cautioned GFDL to "not create additional research efforts that are subcritical or place more demands on already stretched resources and support." For the atmospheric part, Ming Zhao's dedicated work has led to the achievement of AM4 under the guidance of Isaac Held. With the retirement of Held, it is not clear who will step up. GFDL may not have the depth of experience to sustain the leading position of FV3. Reviewer 8 was concerned how the dynamical core will be maintained. Reviewer 6 observed that GFDL "hasn't articulated clearly their plan in atmosphere model development in the next five years, but such planning is very much needed for matching resources with targeted development."

Overcoming the lack of specific expertise within GFDL in certain areas may be addressed by collaborations. As GFDL enhances its model development activities, Reviewer 8 suggested developing graduate courses with Princeton University to develop in-house experts in numerical modeling. Clearly, there is some overlap in various component of the climate and Earth System model developed at GFDL and elsewhere (NCAR, DOE, and NASA). As modeling efforts demand large resources, GFDL should actively look into how it can leverage other modeling efforts, especially in topics that GFDL lacks in personnel. Currently, GFDL's SIS2 sea-ice code borrows from the CICE consortium, which is a good strategy. In the assessment of Reviewer 2, "there is duplication of effort in land and biogeochemical model components, and GFDL's relative short-staffedness in atmospheric boundary-layer turbulence, clouds and aerosol/cloud interactions could be balanced by collaborations in these areas with NCAR, GISS, and academic partners."

As part of a mission agency, GFDL transfers 15-20% of its base funding in a Cooperative Agreement with Princeton, i.e. CIMES. As such, this necessitates that GFDL's "first order collaborations" is with post-docs, students and long-term scientists at CIMES. The Panel would encourage GFDL to engage in significant collaborations with other institutions when there are mutual interest and sustained resources. While recognizing GFDL's need to be focused in its approach, the Panel also wishes GFDL to adopt an open-development paradigm similar to MOM6 for other model components, to the extent feasible within the funding constraints. Additionally, if GFDL simulations could be made accessible to the outside community, the broadened usage would enhance GFDL activities in areas that would benefit from community engagement. Reviewer 2 suggested that "having a curated set of outputs from other selected GFDL simulations might stimulate broader collaboration that could provide valuable feedback and intellectual resources to the Lab."

The Panel noted collaborations that GFDL is undertaking with other parts of NOAA. Reviewer 1 was encouraged that GFDL scientists are already collaborating with ESRL colleagues on certain applications like seasonal prediction using statistical techniques based on analogues and marine ecosystems. For the latter application, they have well-defined stakeholder needs at NOAA NWS, NOS, NMFS and NESDIS. Embedding NCEP and NMFS scientists at GFDL is an additional positive step towards cementing ties with other line offices in NOAA.

The Panel also encourages GFDL to strategize how to approach its model configurations. Reviewer 9 noted that although the Earth System is a complex coupled system, not all coupling is needed to address different problems using ESM. Furthermore, Reviewer 9 suggested doing "research to identify important earth-system feedbacks and distinguish them from processes/variables of important societal impacts but of little feedback onto the physical system. This will help set priorities in ESM development and research." Reviewer 6 added "while significant advances have been demonstrated in the SHiELD model, future research would benefit from more strategic discussion and planning of how convective-scale modeling may support both weather and climate research. This will be an important consideration for the future evolution of the unified model system."

The Panel suggests GFDL not lose sight of the value of simplified models to investigate basic processes in its push to advance Earth System model. Reviewer 8 reiterated the learning values of having GFDL models with "an option to conduct idealized and simplified experiments such as aqua planet experiments or radiative convective equilibrium." More specifically, Reviewer 9 suggested developing a light version of CM4, something like SPEAR with CM2.1 resolution. "This allows graduate students and postdocs at universities with limited computing resources to explore climate dynamics with a state-of-the-art model (except at lower resolution)." Additionally, this modest investment enables GFDL to tap into a large community to test and improve CM4. The feedback from a wide user base on CM4 physics is useful for GFDL model developers to improve the model and its performance.

Finally, the Panel offers suggestions for the continued utilization of existing observational data toward GFDL modeling improvement. Reviewer 1 envisioned that "some of the land-modeling effort can benefit by the extensive observations being made elsewhere, e.g. National Ecological Observational Network (NEON), sensors in the soil projects that are NSF-funded." In evaluating and improving regional aspects of global model with the high-resolution FV3 dynamical core, simulated clouds and precipitation for various weather events can be compared with local ground-based measurements and satellite observations. Reviewer 8 opined that these efforts are "new areas of the model development, in contrast to the development of conventional GCMs by using climatological fields of observations."

(b) Theme 2: *Understanding Earth System Phenomena*

Quality of Theme 2: GFDL conducts world-class research to help better understand Earth System phenomena. It accomplishes this by leveraging the insights of its scientists and the Lab' unique expertise in model development. The research products are of highest caliber as evidenced by the quality of publications. As assessed by Reviewer 3, the outcomes of GFDL work "provide scientific foundation for Earth system modeling, predictions, and projections." Reviewer 5 stated that presentations under this theme "were convincing that the research was very high quality, with direction and conducted by highly competent and motivated scientists and support teams."

In partnership with Princeton, GFDL's involvement with the NSF-funded SOCCOM project has further enhanced the quality of this theme. SOCCOM is yielding new insights on the Antarctic Circumpolar Current (ACC), shelf processes, open ocean dynamics, as well as the role of the Southern Ocean on the carbon cycle. The team continues to publish influential papers on these topics.

The Panel admired the interconnectedness between scientific research and model development at GFDL. Reviewer 2 attested that the GFDL group is not one "to shy away from following ideas that come out of its climate model simulations. A long-standing part of lab culture is to systematically understand the model configurations generated by new GFDL model development. This leads to interesting basic science." Reviewer 4 further noted that "GFDL has a long history of combining models and observations to expand our understanding of the processes governing the atmosphere and oceans, with the explicit feedback on model development." For example, the development of FV3 capabilities at very high resolutions with varying grid configurations will lead to new research avenues.

Through this approach, Reviewer 1 felt that "GFDL is making great strides in contributing to the understanding of natural modes of variability (e.g., ENSO, PDO, AMOC) as well as biogeochemical cycles." Reviewer 2 assessed that an emergent "interesting basic science feature is the hundred-year cycle of Southern Ocean deep mixing in SPEAR, which was deftly used as a hypothesis for explaining the spatial structure of recent sea-ice trends around Antarctica." Reviewer 9 added: "Another important achievement from GFDL is the recent result that the North Atlantic Oscillation, a mode of atmospheric internal variability, can force the coherent Atlantic Multidecadal Variability." Reviewer 6 further stated that the Lab has contributed to "improving understanding of the role of aerosol/chemistry in climate change and developed a unique dataset towards understanding of the long-term dynamic global river N loads to the coastal ocean."

Relevance of Theme 2: Scientific understanding that has resulted from GFDL research activities clearly tackles problems that are societally relevant and address national needs; GFDL's work in Theme 2 continues to be relevant to NOAA as well as OAR missions. Reviewer 8 emphasized that "One important subject is the marine ecosystem; whose modeling is important for GFDL to contribute fishery."

Collaboration with entities outside of the Lab attests to GFDL's relevance in this theme. The stakeholders clearly recognized the importance GFDL's work to understand the Earth System. Specifically, Reviewer 4 found that the partnership with the SOCCOM project (led by Princeton University) "seems very effective and with a strong endorsement of GFDL's importance to the project by the PI. Similarly, the potential from the collaboration with VULCAN on machine learning indicates the strong relevance of the modeling capabilities for understanding processes." Reviewer 2 raised the point that much of the relevance from GFDL's work on understanding climate model phenomena "will ultimately be documented by users of the CMIP6 archive who can explore regionally relevant phenomena more thoroughly than GFDL scientists have the bandwidth for."

The Panel expressed some reservations on how GFDL will maintain future relevance in this theme. Individual intellectual curiosity seems to drive the research on predictability of the Earth System. Reviewer 2 cautioned that "some issues might merit more attention, e.g. a better understanding of aerosol radiative forcing including aerosol-cloud interaction in the AM4/CM4 simulations, which is important to interpreting observations and simulations of the historical period." Reviewer 8 believed that GFDL, in moving forward, still needs to improve in clarifying which specific areas of the Earth System would be focused. Based on the 2014 Review Panel recommendation that GFDL "needs to develop a concrete plan for near- and long-term Earth System model development in the areas of land surface modeling, atmospheric chemistry, and marine biogeochemistry," Reviewer 8 did not understand how GFDL has decided on such a plan. The information presented during the current review on the scope of Earth System did not squarely address that recommendation. Without seeing a clear strategy of GFDL's Earth System focus, the reviewer believed GFDL's relevance in understanding Earth System phenomena may be compromised.

Performance of Theme 2: The main GFDL directives are to support a key NOAA mission to understand and predict changes in climate, weather, oceans and coasts; and priorities such as the Weather Act and Blue Economy, as well as OAR vision of driving scientific innovations, detect changes in the ocean and atmosphere, and better exploration of the marine environment. Progress made under this Theme has demonstrated that GFDL has more than met their directives.

With respect to "Leadership and Planning," GFDL has a well-organized strategic plan relevant to Theme 2. In response to previous 5-year review, GFDL has focused on areas in which it can have the most scientific impact, harvesting available resources. Reviewer 1 remarked that "one must have strong foundational understanding of phenomena, their variability either inherent or forced, before getting in the business of making predictions." In this regard GFDL "is taking a deliberative and thoughtful approach to predictions, either sub-seasonal, seasonal, or longer." Reviewer 2 noted that the Lab is providing some leadership to the community in participating in relevant MIPs (associated with CMIP6) to gain new insight into processes like cloud feedbacks and radiation.

With respect to "Efficiency and Effectiveness," GFDL shines. GFDL scientists are individually excellent at model interpretation. In conjunction with the graduate program at AOS Princeton University, GFDL helps train students in using models to gain physical understanding. Although the total number of scientists/students is small, the effort has produced a large amount of significant results. The bias reduction performed to CM4 is exceptional work. Reviewer 4 saw this as "a testament to the ability of the GFDL scientists to systematically solve the problem and reflects GFDL's experience in atmospheric processes."

The Panel expressed the need for additional external collaborations in addition to those at Princeton, to help push the envelope in using current GFDL models for understanding phenomena. Reviewer 2 noted that "this reflects a somewhat 'insular' culture with plenty of internal collaboration, but deliberate resistance to the perceived distraction that might result from increased external collaboration." Through subsequent discussions at the review, and materials received post-review, the Panel recognized GFDL's model development cycle involves ~5 years for significant scientific advancements to occur in modeling. This disfavors in general collaborations that are not aligned with the long-term mission. It was also recognized that GFDL has dozens of collaborations as reflected in over 50 multi-authored publications in 2018 alone. These are co-authored with scientists from academic institutions, private institutions, other parts of OAR, and other agencies. GFDL has participated in the annual U.S. climate modeling summit, as well as the interagency Climate Process Teams.

The Panel realized that GFDL is in a distinct phase at the time of this five-year review and, consistent with the CMIP and IPCC AR6 cycles, much of the personnel time has been spent in the past ~5 years in the development of models, as has been the case at other modeling centers around the world. Papers on the models are just now (~past 10 months) making their appearance in the peer-reviewed literature. After this will come the phase of their utilization for addressing important scientific questions (e.g., aerosol-cloud-climate feedbacks and sensitivity) and prediction investigations. In fact, these endeavors have already begun but not complete or paper-ready at the time of this Review. In contrast, the 2014 Review occurred a time when the then GFDL models (Series 3 plus FLOR and HiFLOR models) had been fully exercised in the applications-cum-predictions mode; the parent models had already been developed a few years prior. There were thus numerous peer-vetted applications available for demonstration ("understanding") with the CMIP5-era models back in 2014. That understanding has resulted in vastly superior models now in 2019.

Regardless, GFDL is in a unique position to address the equilibrium climate sensitivity (ECS), especially as the ECS of CM4 and ESM4 spans much of the emerging range across CMIP6 models. This problem is very relevant to NOAA and the nation. Reviewer 4 concurred that ECS inconsistencies between CM4 and ESM4 highlight new challenges that Earth System models bring. Lastly, while studies related to the Earth System model shows good scientific results, Reviewer 8 noted contributions to cloud and circulation studies were missing. This has been a strength of GFDL and have garnered respect to the Lab from the community.

Recommendations for Theme 2: The Panel hopes that GFDL not lose sight of its strength in understanding of Earth System as it makes future investments in this theme. Reviewer 5 stressed that GFDL maintains "areas of strength, but in particular the high-quality research in the area of this theme which has its roots in the pioneering work of Manabe." However, this will be difficult as GFDL continues to support NOAA missions and maintain balance between breadth versus depth in its activities.

Maintaining its strength in this theme will require GFDL to have adequate human and computational resources. For the latter, the Lab would need sufficient computing resources to help achieve breakthrough understanding in the next 5-year period. For the former, careful planning will be required as suggested below.

The recent personnel departures at GFDL may potentially undermine the Lab's role as a leader, especially in its flagship atmospheric dynamics. Reviewer 4 cautioned that "some of those people are literally irreplaceable by a single person, but a strategic combination of hires in the field of atmospheric physics and dynamics seem necessary." Reviewer 8 expanded on this point in mentioning that "dynamical meteorology is always the core area of the atmosphere and climate studies, even though as Earth System models become [more] comprehensive and complicated. GFDL should keep a few high-quality researchers in the field of dynamic meteorology." Reviewer 1 also reminded the Panel that "at some stage the funding for SOCCOM will end, and the Lab needs to begin planning for the post-SOCCOM phase." The Lab needs to remain engaged with existing collaborators in that project.

At present, the Lab may be subcritical in terms of having a critical mass of subject matter expertise in specific areas. A recommended strategy to address this issue is through partnerships. GFDL needs to be agile in terms of making temporary (i.e., tactical) partnerships to achieve its future strategic goals. Reviewer 1 urges GFDL "to identify such gaps, be somewhat opportunistic and address in a timely manner so that their effort forges in the right direction."

The Panel also noted a few scientific recommendations to help sustain GFDL strength in this theme and remain relevant. Reviewer 8 strongly suggested that "GFDL should keep the high standard of the cloud and circulation studies in terms of their deeper understanding in the Earth System. Use of simplified or idealized models such as aqua planet experiments or radiative convective equilibrium is prerequisites to such studies." Reviewer 7 urged GFDL to increase efforts of incorporating the stratosphere into mainstream GFDL research as the Lab looks to better understand basic processes, weather and climate extremes, and climate change. These efforts might help lead GFDL to address persistent stratospheric bias problems in models that fully resolve the stratosphere, and, as a by-product, improve tropospheric predictability and projection (addressed in Theme 3). Reviewer 6 suggested that additional investment and encouragement of research on GFDL's key initiatives (e.g., "cloud-climate interactions" and "weather and climate impacts") could lead to more significant progress in the next five years. Finally, in light of "GFDL's gained expertise in understanding of some complex long-standing issues related to connections between aerosols, clouds, convection and climate connections," Reviewer 3 saw an opportunity for GFDL to understand phenomena related to ECS, "which is very topical especially in light of the latest CMIP6 outcomes."

(c) Theme 3: *Earth System Predictions & Projection*

Quality of Theme 3: The main thrust under this Theme is toward prediction and projection, with the justification that the Earth System is highly coupled across spatio-temporal scales and that an integrated modeling system can address weather and climate across time scales. Reviewer 6 commented that GFDL has made "huge progress in testing and evaluating the unified model system for predictions across timescales from weather to long-term climate projections. The skill of their predictions across the broad range of timescales is world leading and is a testament to the effort of the model development team."

Activities under this theme should help us better understand and simulate processes across different timescale and "cutting-edge topics like hydroclimate variability and predictions" according to Reviewer 3. Reviewer 2 remarked that "GFDL's unified model suite provides great NOAA-relevant capabilities for predictions and projections of a wide variety of important phenomena impacted by climate change, such as severe weather, tropical cyclones, drought/flood, sea-ice retreat, sea-level rise, ENSO, marine ecosystems, wildfire, etc." The presentations during the review clearly demonstrated preeminent research on prediction and predictability. Reviewer 8 recognized the numerous "high-impact papers are published for tropical cyclone projection and attribution."

The Panel noted key accomplishments in this theme that reflected quality. Reviewer 8 stated that experimental results of subseasonal-to-seasonal (S2S) and seasonal-to-interannual studies are impressive, yielding good reproducibility of MJO and seasonal forecast of tropical cyclones (TCs) with SPEAR. Reviewer 9 noted that FLOR is the first seasonal forecast system with skill in predicting regional patterns of TC track density and landfalling TCs. Furthermore, HiFLOR shows skill in simulating and predicting major hurricanes. As Reviewer 2 stated, together with a top-notch ENSO simulation, the accomplishments make "GFDL best in class in the U.S. in its capabilities at seasonal to decadal scale prediction of both the physical climate system and its impacts on natural ecosystems and human-managed systems."

Notable technical advancements with recent model configurations have further enhanced quality in this theme. Reviewer 9 noted that the "FV3-based SHiELD offers high-resolution extended weather forecast (especially with nested domains and/or stretched grid), in synergy with SPEAR S2S predictions." Reviewer 2 identified that the "lightweight ocean data assimilation system and a simple but effective ocean bias correction [i.e., the Ocean Tendency Adjustment] help with coupled initialized forecasting."

Relevance of Theme 3: GFDL products from this theme directly align with the mission of both NOAA and OAR; they have strong relevance to centers within NCEP as well as Fisheries. GFDL regularly contributes CM2.1 and FLOR forecasts to the North American Multi-Model Ensemble (NMME) and S2S projects, and to fisheries related ocean forecasts. Reviewer 9 speculated that "ESM4, properly initialized, has the potential to contribute to predictions of air quality, marine environment and fisheries."

The Panel found presentations involving ESM4 effective in demonstrating GFDL connections to the NOAA mission of managing ocean fisheries and protecting sensitive marine ecosystems. "Clearly, unified prediction from weather to climate timescales and space scales serves many national needs for evidence-based climate-aware decision-making inside and outside NOAA.", remarked Reviewer 2. In Reviewer 4's opinion, "GFDL research relevant to fisheries was a highlight, and demonstrates the strength and justification for GFDL to be in OAR. Furthermore, this also highlights the importance of having 'stakeholders' (or at least connectors to stakeholders) be physically present at GFDL." Reviewer 5 expressed some disappointment that GFDL contributions to NMME "was said to be a service with no feedback to research, which may be a lost opportunity to evaluate the GFDL product with respect to other contributors."

The Panel clearly recognized FV3 dynamical core as the prominent research product from GFDL that supports NCEP, especially EMC. Reviewer 8 noted that FV3 activities have the potential to open new research avenues in the field of global cloud-resolving regimes, thus further enhancing GFDL relevance in this theme.

Performance of Theme 3: With respect to "Leadership and Planning," GFDL has the right strategy to pursue prediction and projection. In its 5-year strategic science plan, GFDL has clearly laid out key research foci that will leverage the unified modeling framework. As remarked by Reviewer 4, "GFDL is nicely pushing some boundaries in terms of biogeochemical prediction. This is a clear success of their approach towards unified earth system modeling." Reviewer 8 further added that the "overall performance of the Earth System Predictions and Projections is outstanding. In each categories of the models (SHiELD and SPEAR), unique results have been produced." Reviewer 9 opined that "GFDL climate models are among the best in the world in reputation and performance. CM4 and ESM4 contribute to the CMIP6 and IPCC AR6. With the top-performance SPEAR in hand, GFDL is poised to maintain the leadership in the important area of understanding and predicting climate variability/change central to the NOAA mission." However, Reviewer 2 noted that "the emphasis at GFDL seems to be on a great long-term climate model, with less emphasis placed on variability metrics (even though the model seems to perform well viewed through such a lens) or issues of initialization of memory components such as land (soil moisture) and sea-ice thickness."

With respect to "Transition of Research to Applications" or R2O, GFDL continues to exhibit concerted efforts to make products and innovations developed at GFDL available toward applications and in support of NOAA and OAR missions. While NCEP is the primarily the "O" in R2O (and a key play in the transition process, the "2"), Reviewer 5 viewed "GFDL is a superior research laboratory and contributions to the 'R' to R2O is perhaps its highest priority and its performance exceeds expectations." With additional NOAA investment, Reviewer 2 thought that "GFDL could turn into the world's best research modeling system for subseasonal to decadal scales and support a similar improvement in operational capability at NCEP." The Panel encourages GFDL to engage with EMC to make the U.S. a world leader in weather to seasonal forecasting, so EMC is on par with ECMWF.

From the presentations, it was clear to the Panel that GFDL is effectively supporting transition of its research to the operational wing of NOAA. It has increasingly added more Operational Services in its portfolio, the latter being mostly unfunded by the agency. All model components, models, and simulation data have been made available to EMC and placed in the public domain this decade, after peer-reviews of the papers and ensuring they meet the Data Quality Act (e.g., CM2.1, HiRAM, AM3, CM3, ESM2M, ESM2G, AM4, ECDA). Soon, this will be the case for the Series-4 models and SPEAR. Currently, the "EPIC" framework consists of model components mainly from GFDL. Other service examples include generously-lent expertise for: software engineering of FV3; MOM6 ocean coupling for EMC's seasonal prediction model; cloud computing methodology; seasonal predictions for Fisheries. The "service" activities constitute an increasing fraction of the base non-HPC budget.

Recommendation for Theme 3: As GFDL continues its approach for Earth System prediction and projections under the unified model framework, the Panel sees a few key opportunities that will enhance GFDL efforts.

Internally, GFDL would do well to foster stronger collaborations within the Lab to maximize returns since Theme 3 cuts across several research divisions. Reviewer 9 thought that "synergy of SHiELD extended weather forecast and SPEAR S2S prediction is a low-hanging fruit, so is the extension of SPEAR to include, judiciously step by step, key Earth system components of large societal impact." Reviewer 2 also noted that proper consideration/efforts and added resources would make "SPEAR into an attractive operational next-gen replacement for CFS." Furthermore, given the encouraging results of the global cloud-resolving regimes facilitated by FV3, GFDL could galvanize internal efforts to lead research studies using global cloud-resolving models (as encouraged by Reviewer 8).

The prevailing sentiment among the panelists is that GFDL should pursue additional engagement with NOAA. Reviewer 4 viewed the "very successful collaboration with fisheries and the downscaling for Climate Assessment are a clear indication that GFDL could consider expanding the range of applications of its models in relation to the NOAA mission." The current engagement between the physical scientists at GFDL and scientists (such as Vince Saba in fisheries) was applauded as being productive. Its continuation is encouraged so cross-fertilization between research and applications is promoted. Reviewer 2 strongly felt that "there is room for GFDL to pursue a more aggressive collaboration strategy with other partners in NOAA and elsewhere in improving our national modeling capability for initialized global predictions, while still protecting its intellectual environment as a place [where] scientists can focus deeply on excellence." The reviewer encourages GFDL to pursue additional collaborations, as appropriate and feasible. Given the outstanding progress related to high-resolution FV3, collaboration with NCEP for the operational modeling should be considered. Reviewer 6 suggested GFDL and the NOAA prediction centers should look for more ways to facilitate transitions from research to operations. The Panel encourages GFDL be more involved in EPIC to further support NOAA.

At the same time, the Panel cautions GFDL about being overextended. If GFDL invests in further improving forecast skill of operational models, Reviewer 8 suggested that GFDL should avoid being too devoted in technical improvements. GFDL should "approach the improvement from the scientific side. Very technical studies related to the assimilation are not suitable topic in GFDL." Reviewer 2 observed that "GFDL rightly is cautious about entering partnerships in a 'service' role, but that caution assumes that they will not get adequately resourced to make this a good thing for them intellectually."

Finally, the Panel sees room for GFDL to advance prediction and projections through the usage of satellites and incorporation of the stratosphere. The Panel would have liked to see details on the efforts to analyze satellite data, particularly those related to clouds, precipitation, and radiation. Reviewer 8 remarked that the "result from the high-resolution simulation of the DYAMOND by FV3 looks similar to the geostationary satellite. The direct comparison of the cloud fields between the model and the satellite observation data is possible. GFDL should think about a strategy of using satellite data for evaluation and improvement of the models." Stratospheric process may play a role in atmospheric predictability beyond two weeks. Hence, a few panel members wanted to remind GFDL to not ignore the stratosphere if it wants to be at the leading edge of S2S prediction. Reviewer 7 noted that GFDL "would be remiss by not paying enough attention to the potential role of stratospheric predictability." Reviewer 4 suggested that GFDL either expand its stratospheric group (currently 1 person) or collaborate with external groups like NASA, NCAR, UKMO and MPI who have extensive efforts in that topic.

4. Summary of Laboratory-Wide Findings

As the Lab looks forward to the next five years, the Panel generally found GFDL to be in great shape at this juncture. In this section, the Panel synthesizes its overall findings, as agreed upon by the majority of panel members during the Panel's executive discussions. These findings are organized into three basic areas: uniqueness, strength, and challenges.

During the visit, the Panel asked GFDL to self-identify its unique attributes; however, at least a couple of panelists did not find the presented rationale compelling. The Panel was able to identify unique aspects of the Lab: GFDL addresses NOAA's mission goals in weather, climate and earth system modeling, as well as science consistent with NOAA's adoption of the Pasteur's Quadrant principle as depicted by the slide shown during the Review.

Panel members clearly recognized GFDL's long-standing intellectual capabilities to address fundamental processes in climate physics. Coupling this with expertise in model development, GFDL is poised to continue making meaningful contributions through its Earth System models by providing societally relevant predictions and projections consistent with NOAA and OAR missions. Past efforts have already resulted in scientific and technical products that have been adopted across NOAA as well as the greater community. Furthermore, GFDL has forged meaningful synergy with Princeton University and the embedded graduate program with Princeton University. The Cooperative Institute, CIMES, offers GFDL an unparalleled ability to harvest new intellectual talent and to explore new opportunities afforded through an academic setting like Princeton.

Rooted in the pioneering work of Manabe, GFDL possesses core strengths that align well and remain relevant with NOAA and OAR missions. GFDL personnel possesses strong intellectual abilities and insights; they combine scientific inquiry with forward-thinking model development – a combination that truly sets GFDL apart from other NOAA labs. The Panel noted that even as prominent scientists, (e.g. Isaac Held, S. J. Lin, Gabe Vecchi and Ron Stouffer among others) have either retired or left the lab, promising early career scientists have recently joined the Lab. These new staff have contributed and sometimes led the modeling effort. Thus, just as GFDL successfully endured past retirements and departures, the Panel anticipates that GFDL will continue to do so in future.

Coupling its scientific and technical expertise with a team-science approach, GFDL has produced world-class model products (e.g., CM/ESM4 configurations). Components such as FV3 are crucial to NOAA. The Panel saw the open development approach of MOM6 as a new strength that can be widely adopted by

GFDL's future efforts and can encourage new collaborative avenues, thereby broadening participation. The Panel also saw GFDL's progress toward a unified modeling framework for prediction and projection as an emerging strength.

The Panel recognized some potential challenges looming ahead. Given the Lab's current facility, operating budget, and the federal bureaucracy within which it exists, maintaining the afore-mentioned strengths and uniqueness will be difficult in future. The building at Princeton's Forrestal Campus is outdated and provides less-than-ideal working conditions. In dealing with its relatively flat budget, GFDL faces uncertainties in HPC resources and staffing. Meeting the goals of GFDL's next 5-10-year strategic plan will demand increasing computational resources and human expertise (especially in areas that are already subcritical). Existing federal policies and procedures limit access to data and computing facilities to certain staff and produce the unintended consequence of hindering the recruitment and retention of scientists (more on this issue below).

The Panel initially struggled to gain understanding of the collaboration with external entities. However, upon further examining the information provided (e.g. list of publications co-authored with external partners, and extent of collaboration over CMIP6), the Panel was satisfied that GFDL was doing a fine job in maintaining robust long-term partnerships with relevant entities within the mission needs of NOAA, and current funding constraints.

The Panel recognized the challenge GFDL faces in managing a workforce that comprises the following: three different employers (and thus three different chains-of-command), viz., federal employees, staff from Cooperative Institute (CIMES), and contractors (SIAC, UCAR). Some staff expressed concerns on the apparent "uneven" treatment; however, the Panel was of the opinion that such perceptions are a result of complex multiple-employer structural chain at the Lab. As evaluating workforce issues was not part of the charge for this Review, the Panel mentions this in passing as the topic came up in closed meetings.

Nonetheless, the Panel noted positive steps GFDL has taken over the past 5-year period on workforce demographics and gender diversity. Several committees have been set up over the past 5 years to facilitate a wide range of participation by the Lab's residents – their chain-of-command and employer is irrelevant for this purpose. There are women on Committees for awards nominations to professional societies; internal awards have been won by two women over the past 3 years, and appointments of women have been made to the Research Council. GFDL has hired an increasing number of women and veterans. Women have been put up for awards in NOAA, DOC, and professional societies, and sponsored for NOAA science functions.

Training opportunities for early and mid-careers have been provided for Federal scientists; this has included a recent Ph.D. obtained by a woman scientist from Rutgers while continuing to work at GFDL. GFDL also recently promoted the first woman to the Senior Scientist position. The Panel also learned that a room has been permanently reserved for nursing mothers. The Panel applauds GFDL for taking pro-active steps to ensure work-life balance for its employees. Unfortunately, due to the current slow pace in federal hiring practice, the Panel learnt GFDL lost five women in the past four years.

Lab management seemed aware of the broader problem of the low representation of underrepresented community in the Geosciences nation-wide, starting from the undergrad, graduate going all the way to postdoc level and beyond. One noteworthy GFDL effort is to attract persons from minority-serving institutions by bringing them in as summer interns to be exposed to GFDL. These efforts have resulted in some gain.

Internal issues related to parental leave, hiring, and data security/access, are tied to governmental policy. Clearly, present policies on federal parental leave are hindering the retention of women and affecting the quality of work-life balance. The Panel was made aware of the inordinate delays in the hiring process and difficulties in accessing work-related data and computing behind the NOAA HPC firewall from abroad. Such issues have greatly impacted the efforts of foreign postdocs or staff who left GFDL, CIMES or Princeton, as they were completely cut off from the data/computing needed to complete work started whilst at GFDL. The Panel is cognizant of the fact that some of these issues are beyond the purview of GFDL, OAR and NOAA. For example, federal parental leave is determined by Office of Personnel Management.

5. Summary of Recommendations

Based on the challenges envisioned above and recommendations noted in Section 4, the Panel offers key actionable recommendations for GFDL and OAR as GFDL embarks on its activities in the next five years. Taken positively, these recommendations might steer GFDL toward new opportunities that the Lab can truly capitalize upon. NOAA OAR should continue nurturing the incredible talent at GFDL – allowing the scientists to focus on the science and applications that the Lab sets out to accomplish. GFDL and its scientists are performing a vital task for NOAA and the nation. This nurturing process should involve working with GFDL management in addressing issues related to paid leave, hiring, computing security, and data access/management.

- **Strengthen internal collaboration within GFDL/Princeton.** The Panel commends GFDL for its close collaboration with CIMES and Princeton. The Panel noted existing robust collaboration with Princeton. This is evidenced by co-authored papers with each one of the four Faculty members from Geosciences and Princeton Environment Institute who are in the AOS Program. In addition, there are collaborations and regular scientific meetings with Faculty from each one of the following Departments: Applied Mathematics, Princeton International Institute for Regional Studies, Civil Engineering and Water Resources, Woodrow Wilson School of Economics, History, Ecology and Evolutionary Biology. Finally, there are collaborations with 2 Faculty members from Rutgers, the other neighboring main University. The Panel encourages the Lab to continue to foster and further strengthen such collaborations in addition to sustaining strong internal cohesiveness. This is essential to success.
- **Promote a culture of diversity, equity, and inclusion.** In closed sessions with GFDL leadership, it was clear that the Lab management is aware of issues that the Panel heard expressed during closed sessions. GFDL leadership is working on these issues, within the constraints of federal

rules. The Panel acknowledges the complexity of managing the GFDL workforce comprising feds, Princeton staff and contractors. In discussions with staff, there was seemed to be a lack of understanding on how leadership has taken steps to navigate through issues to the best of its ability. The Panel suggests lab-wide communications through periodic town hall meeting, on-boarding processes so misconceptions are alleviated.

The Panel realizes that GFDL adheres to federal practices related to paid leave, hiring, security, and data management. Nevertheless, on behalf of its employees, GFDL leadership as well as OAR could internally advocate for the improvement of support for new parents, expediency in hiring practice, and improved computing/data access. In addition to listening to concerns, proactive support groups can be formed to explore creative internal solutions and formulate contingency plans. For example, providing time-limited, secured access to GFDL computing and data archival outside the NOAA HPC firewall might be explored.

- **Be ready to reach out to outside entities**. GFDL should avoid duplicating efforts in Earth System model developed elsewhere like NCAR, DOE, NASA, UKMO, and MPI to the extent possible and appropriate. For example, some redundancy and duplications already exist in land and biogeochemical model components as well as in activities in atmospheric boundary-layer turbulence, clouds and aerosol/cloud interactions. The Panel recognizes there is considerable risk in the proposed approach since borrowed components may not be readily transferable. Likewise, GFDL should be aware of missing or inadequate efforts that might hinder its strategic plan, e.g., the role of stratospheric processes in atmospheric predictability beyond two weeks.

  In topics where GFDL lacks personnel or expertise, the Panel highly recommends GFDL to make tactical partnerships with appropriate external groups within the U. S. and international scientific communities and to welcome collaboration with other U.S. research groups outside of Princeton.

  The Panel urges OAR to consider additional funding to pursue such proposed new partnerships and community outreach activities that will eventually benefit NOAA mission. Currently, the collaborator network favors people who have worked or studied there or at Princeton. The Panel also noted the current firewall in computing environment does not facilitate cross-fertilization with external collaborations. Improved model documentation and facilitating sharing of model simulations will be a step in the right direction.

- **Increase engagement with other NOAA efforts.** The Panel encourages GFDL to advance its working relationships with other groups within NOAA. Current physical embedding of EMC and NMFS scientists at GFDL has brought meaningful collaborations and promoted cross-fertilization of ideas. The Panel suggests that GFDL be more involved in EPIC and take on more of a leadership role to further support NOAA. Given the outstanding progress related to high-resolution FV3, continued collaboration with NCEP for the operational modeling should be considered.

  Again, the Panel suggests OAR provide additional funding for such participation, since this will eventually benefit NOAA mission goals.

- **Define appropriate scope toward model development**. GFDL should strategize how to approach its model configurations. Not all problems are best addressed using a fully coupled ESM. GFDL should not lose sight of the inherent values of simplified models (or lighter versions of recent model configurations) to investigate foundational processes and accommodate wide usage especially in academia. In maintaining its NOAA/OAR missions, based on the talent pool available and provided NOAA budget, GFDL should self-impose realistic expectations and focus on a targeted set of its modeling systems suitable for operations and applications. Reiterating the Panel's recommendation for Theme 1, GFDL must exercise care to ensure its preeminence in research and its core strength in climate physics. The Lab should leverage its core strength and address these self-imposed expectations from a scientific perspective.

  The Panel is aware there is much more to do in the area of clouds-convection-microphysics-radiation to improve understanding of climate forcings, feedbacks and sensitivity. Nevertheless, GFDL scientists have made substantial contributions on these issues during the past five-year period. The GFDL community publishes approximately 200 papers/year. The Panel applauds GFDL scientists for their world-class contributions towards advancing the state-of-the-science on clouds-convection-microphysics-radiation. For example, the 2016 paper in the Journal of Climate by Zhao et. al was the recipient of the 2017 OAR Outstanding Paper award.

- **Incorporate existing observational data toward GFDL model improvement.** Some of the land-modeling effort would benefit from the extensive observations being made elsewhere (like NEON). Efforts to analyze satellite data for evaluation and comparison of model results should be strengthened, particularly as related to clouds, precipitation, and radiation. Direct comparison of the cloud fields between models (like DYAMOND) and satellite observations on weather time scales is possible. GFDL should strategize how to use satellite data and observation networks in new ways for model evaluation and improvement.

- **HPC challenges and opportunities.** HPC crosscuts all three themes. The Panel anticipates that the Lab will face several challenges on the HPC front. In particular, GFDL will need sustained HPC resources to address issues such as code conversions, alternate architectures, machine learning and production runs for the climate assessment efforts on IPCC, WMO, and NCA. GFDL scientists have taken a leadership role in past assessments. The Panel believes GFDL will make significant contributions to the assessments that are useful to the agency as well as the nation.

  GFDL is the go-to lab in NOAA for modeling needs and to maintain its top-notch stature. The Panel urges NOAA OAR leadership to provide adequate HPC resources. Some of the above recommendations hinge on NOAA resource and accommodations. To this end, the Panel makes the following recommendations to NOAA and OAR leaderships. The Panel strongly recommends that NOAA consider making additional investments in computational resources, software engineering, and building infrastructure to help GFDL address the goals set out in its strategic plan. Additional capacity for GFDL model output archival and analysis and for computation with GFDL models outside the NOAA HPC firewall would greatly facilitate GFDL collaborations with researchers not just at Princeton and CIMES, but elsewhere around the country as well. NOAA leadership could work with CIMES and Princeton University to explore creative and viable options for facilitating this investment.

Lastly, based on data and statistics provided to the Panel, GFDL is anticipated to soon grow to a size that would make the current building unsuitable since the outdated space would provide less-than-ideal working condition.

6. Feedback on the Review Process

The Panel recognized the enormous effort of the GFDL leadership, staff at the Lab, CIMES and Princeton AOS. Materials made available prior to the meeting were very helpful as were discussions during the site visit. The Panel thanks lab staff for being flexible to the needs of the Panel during the visit since this greatly facilitated the review process. The Panel also appreciates the clarifications and documents provided post the site visit.

The Panel was pleased to hear the overall high-quality presentations with representations from various groups and appreciated meetings with early career and recently arrived scientists. Overall, in addition to stakeholders at the meeting, the Panel met with more than half of GFDL and GFDL-related staff. All GFDL personnel extended support to the Panel. Reviewer 9 remarked that "having the venue on Princeton main campus within the walking distance from Nassau Inn is great. The spacious lobby allowed interactions with lab scientists and NOAA representatives during breaks."

Regarding the review process, the prevailing sentiment was that the schedule was jam-packed and intense, with 14 hours a day of meetings. Reviewer 2 remarked that such scheduling "made for a hurried and less well-considered group consensus process, although in the end this probably did not affect our review much." Reviewer 1 admitted "I don't have a suggestion on how it could've been less hectic without going over and having an additional day. I think, as is, it worked well." The GFDL community comprises ~200 staff including scientific, technical and administrative staff. This is about 45% of combined ESRL staff. Each ESRL division has a 2.5-day review visit. Just by that metric, it seems like the GFDL review should have been at least 3 full days. This would permit some optimal time for Q&A.

However, other reviewers offered suggestions for improving the meeting logistics. Reviewer 4 would "limit the number of 15-min talks and considerably expand the discussion times, although it was very good to see presentations by a wide swath of the staff…but generally it would be useful to get more one-on-one from the staff." Reviewer 7 added that "relaxing the schedule between themes a bit" would "give the Review team time to reflect, draft notes, and exchange opinions." Reviewer 9 opined that "Some of science talks may be consolidated to provide a big picture of major achievements in the context of vision for future plan." "What is it that the Review Panel can learn only here what they wouldn't have learned at a regular conference?", wondered Reviewer 3.

Despite the large volume of materials presented over just two days, a few reviewers noted that some content was missing. Reviewer 5 found that the presentations did not illuminate materials in accordance with the OAR Laboratory Reviews Evaluation Guidelines (from Appendix B provided in the review materials. Specifically, the guidelines ask some “very specific questions that require knowledge of budget details (e.g., proportion of external funding), divisional plans, and metrics (e.g., publications per FTE/year, citations and service roles) that were not presented in a way to allow the review to provide answers.” Therefore, if future reviews are required to deal with such questions, then specific and targeted presentations are needed (but only with a reduction in other material). Additional useful materials that provided additional clarifications were provided by lab management, post the site visit.

For a future review cycle, some reviewers offered alternative formats for the presentation. Reviewer 4 suggested that a “radical change would be for the Lab to self-evaluate in each of the 3 categories for each theme and then make the case to the review panel.” Similarly, Reviewer 3 wanted an “overview of the Division that summarizes its visions, main activities, achievements, and challenges” as well as “scientific highlights that the Lab is especially proud about.” Such approach “would also offer an opportunity to the Lab to sharpen the vision on its scientific standing and uniqueness.” Similarly, Reviewer 7 “would have preferred that GFDL leadership highlight key accomplishments and their relevance at a high level (i.e., a broad overview), and clearly explain GFDL’s contribution and uniqueness as compared to other entities around the U.S. and the world.” Reviewer 4 concurred that such self-calibration is important and added “it is critical for GFDL to be more open about where their research sits in comparison to other efforts, nationally and globally.” These materials were not available at the time of the review and were subsequently provided to the Panel. Specifically, the GFDL Charter, approved by OAR in 2018, lists the goals of each of the scientific Division at GFDL.

The Panel received a lot of practical instructions prior to the visit. However, during the meeting, there was just one informal breakfast meeting with the NOAA leadership. Some questions emerged during the meeting that could have been best addressed by the NOAA/OAR leadership. It would be useful to allocate a time slot for a more formal meeting of the Review Panel with the NOAA/OAR leadership during the meeting.