2015 – 2020 Review of National Oceanic and Atmospheric Administration, Oceanic and Atmospheric Research, Physical Sciences Laboratory

February 2021

Acronyms and Abbreviations

20CRv3	20th Century Reanalysis
AQPI	Advanced Quantitative Precipitation Information
AR	atmospheric rivers
ATOMIC	Atlantic Tradewind Ocean-Atmosphere Mesocale Interaction Campaign
CaDWR	California Department of Water Resources
CAFS	Coupled Arctic Forecast Systems
CI	Cooperative Institute
CIRA	Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, Colorado
CIRES	Cooperative Institute for Research in Environmental Sciences at the University of Colorado, Boulder , Colorado
CLIVAR	Climate and Ocean -Variability, Predictability, and Change
CPC	Climate Prediction Center
D-ICE	De-Icing Comparison Experiment?
EDDI	Evaporative Demand Drought Index
EMC	Environmental Modeling Center
ENSO	El Niño-Southern Oscillation
ENRR	El Niño Rapid Response
FACTS	FACility for Weather and Climate AssessmenTS
GFDL	Geophysical Fluid Dynamics Laboratory
GFS	Global Forecast System
GEFS	Global Ensemble Forecast System
GFSv12	Global Ensemble Forecast System Version 12
GOES	Geostationary Operational Environmental Satellites
HRRR	High-Resolution Rapid Refresh
LAPSE-RATE	Lower Atmospheric Profiling Studies at Elevation – a Remotely-piloted Aircraft Team Experiment
MHW	Marine Heat Waves
MOSAIC	Multidisciplinary Drifting Observatory for the Study of Arctic Climate
NCEP	National Centers for Environmental Prediction
NESDIS	National Environmental Satellite, Data, and Information Service's
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NSF	National Science Foundation
NWS	National Weather Service
OAR	Oceanic and Atmospheric Research
PACE	Postdocs Applying Climate Expertise
PSL	Physical Sciences Laboratory
R2O	Research to Operations
R2X	transition of NOAA's research outputs into operations, applications, commercialization, and other uses for societal benefits
RFC	River Forecast Center
S2S	subseasonal-to-seasonal
SME	subject matter experts
STAR	Center for Satellite Applications and Research
UAS	unmanned aerial systems
UFS	Unified Forecast System
USACE	U.S. Army Corps of Engineers
WFIP2	Wind Forecast Improvement Project
WRIT	Web-based Reanalysis Intercomparison Tool

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National Oceanic and Atmospheric Administration, Oceanic and Atmospheric Research, Physical Sciences Laboratory

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Review Dates:

November 16 – 20, 2020

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Introduction: Scope and Context of Review

1.1. Background

The National Oceanic and Atmospheric Administration (NOAA) Oceanic and Atmospheric Research (OAR) conducts laboratory reviews of its Physical Science Lab (PSL) every five years to help PSL plan, program, and budget for its strategic planning for its future science development. The review is also intended to ensure that PSL research is linked to NOAA's research mission and priorities and other strategic planning efforts, and meets high quality and performance standards.

A review of the PSL was convened for November 16 - 20, 2020 in Boulder, Colorado. This review took place virtually in 2020 using the technical environments provided by commercial off the shelf products designed to host and conduct online meetings and gatherings. The panel met with NOAA line office leadership, PSL staff, Cooperative Institute (CI) leadership, members of the cooperative institutes, stakeholders, and newer employees over the course of four days of interactions.

A panel of reviewers was identified and requested to serve through NOAA internal processes, with each panel member individually asked to serve on the 2020 NOAA OAR PSL review. A chair was identified to help organize the review panel, and produce this summary report within 45 days of the completion of the November 16-20 review. The chair is required to be a Federal employee. This review summary document represents the independent evaluation from each review panel member who was tasked with producing at least one written evaluation in a research area. This report represents these individual evaluations by the panel and does not represent a consensus review or presentation of the panel.

Prior to the November 16 - 20, 2020 Review, PSL produced a series of presentations focused on thematic areas of focus: predicting extremes, water resources management, and marine resources management. Other presentations included an overall organizational presentation and presentations on observing capabilities, field campaigns, modeling and forecasting, research partnerships, as well as transferring NOAA's research outputs into operations, applications, commercialization, and other uses for societal benefits (R2X). Review Panel members had the opportunity to review each of these presentations prior to November 16 and develop a list of topics for further discussion. The week of November 16 - 20 was then spent meeting with subject matter experts (SME) involved in each thematic area topic of interest, Cooperative Institute and line office leaders and junior staff, and PSL stakeholders.

1.2. Scope and Context

This review covers the PSL research over the last 5 years. The physical science research areas and related themes for review are:

1) Water Resource Management,
2) Marine Resource Management, and
3) Predicting Extremes.

1.3. Executive Summary Key Messages

NOAA received high rankings within the context of quality, relevance, performance, and overall ratings in all theme areas as well as strong support for activities and accomplishments in other areas. The review panel recommends that PSL continue to focus on the development of supporting NOAAs mission—largely in the ways it has been doing so for the last 5 years. For science development and deployment, one main recommendation of the panel is improved coordination amongst NOAA organizations to both help identify priority science and utilize results within models and prediction programs throughout NOAA in a more seamless manner. Other findings of significance include:

- **Predicting Extremes.** Research carried out under this theme is outstanding in many areas. It is leading edge and world class. Individual scientists with strong national and international reputations produce novel and impactful research that contributes directly to the NOAA mission, in particular by bringing process-based understanding to the science of prediction. Recommendations are:

    - NOAA should take better advantage of the portfolio of PSL research and leadership in this thematic area to improve on existing prediction approaches from daily through decadal timescales.

    - PSL research on extremes would benefit from more timely access to the latest code base for NOAA's operational models.

- **Water Resources Management.** Research on flooding contributes to dam safety assessments and research on drought to insights into evaporation, precipitation, and river declines. Recommendations are:

    - Address how the research findings and products using targeted instruments for the California Department of Water Resources (CaDWR) can be extended to other areas in the United States

    - Improve remote sensing for soil moisture to complement *in situ* measurements and improve remote sensing of satellite-based snowpack and snowmelt to yield information suitable for assimilation into the National Water Model and weather forecast models

    - Use PSL's experience with flash flooding in the Western United States to extend flood forecasting to urban areas

- **Marine Resources Management.** PSL has a high-profile impact from developing a firm understanding of many of the important processes involved in ocean and marine ecosystem and management. They lead in developing statistical ENSO forecasting tools, marine heat wave indices, and regional downscaling with interactive models that incorporate species-specific responses and socio-economic impacts. Recommendations are to:

    - Continue work in these areas to support NOAA's marine resources management, particularly with NOAA Fisheries work for exploited species

    - Encourage split-funding scientists to directly bridge PSL and NOAA Fisheries

- **PSL Observing/Field Programs.** This world-class expertise for sensors and radar has grown with Federal funding , effective tenure, and succession planning. Recommendations are to:

    - Identify and encourage interactions among PSL scientists and NOAA modeling centers to assess and improve model realism

    - Use feedback from field work to assess and address any model shortcomings

- **Modeling and Forecasting.** Putting modeling and forecasting in the intersection of PSL's focus areas is appropriate and provides high value. Overall, the broad, deep, and practical approach that connects with observational efforts and projects strongly onto real-world applications and stakeholders is tremendously impressive. Recommendations are to:

    - Provide a more structured or defined interaction between PSL modeling and the predictions systems that their science could improve.

    - Innovative stochastic parameterization schemes are commendable and are showing promising improvements to predictive models. In addition, continued or additional focus on understanding of the physics will help NOAA predict phenomena more accurately.

- **Research Partnerships.** This wide range of collaborations and partnerships is valuable and productive. Recommendations are to:

    - Examine how PSL can identify, prioritize, strengthen, and promote more formal and strategic partnerships rather than ad hoc collaborations

- **Transfer Opportunities (R2X / R2O).** Transferring research project outcomes to operations, applications, and services is necessary to ensure the most advanced science is being provided to support NOAA's mission. This is particularly evident in model improvements, experimental predictions and guidance, and forecasts and projections in ocean environments. Recommendations are to:

    - Focus more on NOAA's operational needs while using PSL's unique position to address user-inspired research

    - Use PSL's unique strength to develop of R2O products for NOAA's line offices

    - Develop ways to transfer satellite data applications and develop products from the research

    - Develop metrics to assess R2X success

- **Cooperative Institute Interactions.** CIs support PSL and allow staffing, expertise, and flexibility beyond a Federal only approach. CIs engage students and promote diversity. Recommendations are to:

    - Coordinate staff training in appropriate and ethical behavior and develop means to respond to negative interactions between PSL and CI staff

    - Work with CIs to maintain alignment of PSL's core research activities and the themes and staffing for the CIs to carry forward in their 5-year cycle of umbrella proposals to NOAA

- **Structure/Operations.** Embedding PSL science staff for a detail within other branches of NOAA and other agencies has been effective in improving and deepening working relationships, which have improved over the last 5 years. Coordination still needs to improve, particularly between groups using the models and those refining the models. Recommendations are to:

    - Create a central access for clear documentation and the latest code base for operational models

    - Create an environment where it is "safe to fail" by re-examining transition plan requirements, priorities, and success metrics

    - Devise metrics for performance evaluations beyond peer-reviewed journal articles that address partnership and R2O activities.

Culture/Diversity. One specific area where the review panel believes PSL needs to focus significantly is the development of an improved workplace culture and diversity. Problems in this area demoralize scientists and staff and harm research efforts. Staff noted issues with bullying and other unacceptable behavior and felt that management was not effectively addressing these issues. Recommendations are to:

- Develop a unified approach between PSL federal employees and all non-federal CI affiliates, contractors, students, and others including education, training, and human resources actions that:
  - Support a civil workplace
  - Encourage bystanders to step in and change the cultural norms
- Establish a human resources process to resolve issues in a transparent manner

1. Individual Panel Evaluation Rankings:

Reviewers were asked to consider the quality, relevance, and performance of the PSL and to provide an overall rating for each research area reviewed, using the following overall ratings:

- **Highest Performance (HP):** In general, the PSL greatly exceeds the satisfactory level and is outstanding in almost all areas.
- **Exceeds Expectations (EE):** In general, the PSL goes well beyond the satisfactory level and is outstanding in many areas.
- **Satisfactory (S):** In general, the PSL meets expectations and the criteria for a Satisfactory rating.
- **Needs Improvement (NI):** In general, the PSL does not reach expectations and does not meet the criteria for a Satisfactory rating. The reviewer will identify specific problem areas that need to be addressed.

In addition, the Review Panel provided feedback and impressions of PSL activities for observing capabilities, field campaigns, modeling and forecasting, research partnerships, R2X transitions, PSL Structure and Operations as well as PSL's culture and diversity.

1.4. Theme 1: Predicting Extremes

Panel Member	Quality	Relevance	Performance	Overall
1	HP	HP	HP	HP
2	HP	HP	HP	HP
3	EE	S	EE	EE
4	EE	EE	EE	EE
5	HP	HP	HP	HP
6	HP	HP	HP	HP
7	EE	S	EE	EE

(HP = High Performance; EE = Exceeds Expectations; S = Satisfactory; NI = Needs Improvement)

1.5. Theme 2: Water Resources Management

Panel Member	Quality	Relevance	Performance	Overall
1	EE	HP	EE	EE
2	EE	HP	EE	EE
3	EE	S	EE	EE
4	EE	EE	EE	EE
5	EE	EE	EE	EE
6	HP	HP	HP	HP
7	EE	EE	EE	EE

(HP = High Performance; EE = Exceeds Expectations; S = Satisfactory; NI = Needs Improvement)

1.6. Theme 3: Marine Resources Management

Panel Member	Quality	Relevance	Performance	Overall
1	EE	HP	EE	EE
2	HP	HP	HP	HP
3	EE	EE	EE	EE
4	HP	HP	EE	EE
5	HP	HP	HP	HP
6	HP	HP	HP	HP
7	EE	EE	EE	EE

(HP = High Performance; EE = Exceeds Expectations; S = Satisfactory; NI = Needs Improvement)

2. Findings:

1.7. Theme 1: Predicting Extremes

Research carried out under this theme is outstanding in many areas, and is leading edge and world class. Research at PSL describes, interprets, and assesses the predictability of weather and climate extremes primarily on time scales ranging from hours to seasons. PSL scientists develop and apply innovative diagnostic methods to advance capabilities to detect, understand, explain, and predict extreme events and trends in the extremes. Many of the individual scientists working in this theme are known nationally and internationally as leaders for their scholarship. Their work is novel and is published, highly cited, and presented at major national and international scientific conferences. PSL scientists also lead and convene sessions at workshops and conferences and are actively engaged throughout the community.

PSL presentations highlighted several specific examples of impactful work of relevance to the NOAA mission. These included the production and distribution of an innovative 20th Century Reanalysis product, which is used throughout the community to investigate and understand the physical system based on nearly 200 years of data. Other examples included: the foundational contributions to the theory of extreme value distributions; the development, implementation and evaluation of stochastic parameterizations in fully coupled models and prediction systems; pioneering development of Linear Inverse Models and their application to quantify potential forecast skill and identify and exploit forecasts of opportunity; innovative diagnostics for weather and climate variability; the development of new statistical forecast models; and work to improve existing NOAA system to advance the prediction of extremes.

Only by understanding the physical system is it possible to build the tools that will enable better prediction, including prediction of impactful extreme events. The collective understanding stemming from PSL research on extremes provides the foundation to create effective and credible scientific knowledge needed to inform policy, planning, and decision-making to manage current and future risks. Work under this theme, therefore, has outstanding relevance to NOAA's mission.

PSL has a specific niche in bringing process-based understanding to the science of prediction—and this is particularly insightful and valuable. Determining the predictability of weather and climate events requires a healthy portfolio of approaches. PSL's leadership in determining the limits of predictability, identifying forecasts of opportunity *a priori*, developing new post-processing algorithms and experimental forecast products for customer evaluation, and advancing real-time event attribution are all clear examples of research fundamental to the NOAA mission that complements and, in many cases, improves upon existing prediction approaches.

Forecasts of opportunity are associated with teleconnections from strong ENSO forcings which occur < 20% of the time. In effect, forecasts of opportunity are high confidence seasonal forecasts. This information is somewhat reflected in current Climate Prediction Center (CPC) outlooks when confidence is indicated as greater than 70%. PSL is in a good position to further develop work that cross-cuts among forecasts of opportunity, limits of predictability, definition of confidence levels for seasonal forecast products.

One aspect of PSL work that the committee did not have time to fully explore was the rationale for the emphasis on subseasonal-to-seasonal (S2S) predictions. These timescales are clearly of tremendous societal importance, so the highlighted research is very appropriate. It is also an appropriate centerpiece of the new draft 2021 - 2025 PSL strategic plan, which is to position NOAA to provide the early warning to inform preparedness for disaster risk reduction, resource management and investments as well as to increase the resiliency of the nation, its ecosystems, communities, and economies by diagnosing the predictability of extremes across multiple timescales. But the last two words are apparently mostly focused on S2S and not beyond, even though there are NOAA efforts in developing prediction systems for longer (e.g., decadal) timescales. PSL research on predictability has a lot to offer there too, and a recommendation would be for NOAA to take full advantage of PSL efforts as seamless prediction efforts are developed and investigated. Some mention of these longer timescale predictions is encouraged to be incorporated into the new strategic plan. Additionally, much of the work presented within this thematic area of extremes, did not necessarily focus on extremes as "low-probability" events as in the outliers of a probabilistic distribution. At least one panel member thinks that increasing activity within these low probability areas would also improve the relevance of PSLs work in this thematic area.

The team of PSL researchers working on extremes is performing very well by all measures. As already mentioned, PSL research in this thematic area is at the cutting-edge. Moreover, it was encouraging to see how PSL-led efforts in stochastic parameterizations are improving NOAA's operational models, and how new statistical post-processing approaches could improve probabilistic prediction of extremes, among other examples. Yet, there is still a sense that PSL science can be more fully integrated across NOAA to realize its full benefit in improved advice and predictions. Perhaps it was because of time limitations and the virtual environment, but it was not entirely clear how developments in theoretical understanding that were undoubtedly being made in the extremes theme were feeding down the line into model improvements. While it was clear that connections between PSL and other stakeholder groups across NOAA are working better now than at the time of the last review (2015), several instances were mentioned where coordination to operational centers and development of the UFS needs to be strengthened. Also, it appeared that aspects of PSL's research on extremes are hampered by lack of access to clear documentation and timely access to the latest code base for NOAA's operational models.

1.8. Theme 2: Water Resources Management

PSL's work on Water Resource Management addresses both flooding and drought precipitation extremes. Time scales for flooding and drought are very different as flooding occurs over hours to days and droughts over months to years. Hence, while work on short-term weather prediction has emphasized flooding, most of PSL's work at seasonal and longer time scales has focused on drought.

The drought-related activities over the last five years have been advanced NOAA products and modeling. A significant highlight is PSL's development of the Evaporative Demand Drought Index (EDDI) that transitioned to the National Water Center in 2019. Another highlight is PSL's Colorado River state-of-the-science assessment that declining precipitation is the main cause of long-term decline in Colorado River flow.

The Atmospheric River Web Portal provides real-time data delivery of observations along the west coast and within several inland California watersheds. These data serve a variety of users and stakeholders inside and outside of NOAA. Observation analysis emphasis is on the western U.S., particularly the State of California and the multi-state Colorado River watershed. Work on atmospheric rivers (AR) has been ongoing at PSL and its predecessors for multiple decades. It appears that observation-analysis-based improvements in process understanding to reduce uncertainty in forecasting AR-related flooding may be mined out.

PSL has a strong, long-term relationship with the California Department of Water Resources (CaDWR). CaDWR has sponsored research at PSL and its predecessors to fund instrumentation, including established technologies such as gap-filling X-band radars and to develop snow-level radars. A concern is that PSL's Advanced Quantitative Precipitation Information (AQPI) based on targeted instrumentation like gap-filling X-band radars and snow-level radars in California that cannot be extended to other areas of the U.S. where these enhanced observations are not available now and are unlikely to be available in the next 5-10 years.

PSL's modeling work on historical and future precipitation extremes is contributing to the multi-agency and multi-state partnership to assess dam safety.

Opportunities for better alignment with national needs include:

- **Soil Moisture.** Improvements in modeling and remote sensing of soil moisture are key opportunities for innovation in the future. PSL has several efforts related to improving modeling of soil moisture, including data assimilation of soil moisture and linear inverse modeling to identify forecasts of opportunity for soil moisture extremes. The current standard for soil moisture measurements uses a probe in the ground. PSL has done some work with sensors on towers and unmanned aerial systems (UAS) and in evaluations of satellite-based soil moisture. Improving remote sensing of soil moisture would provide regional information that would complement *in situ* soil moisture measurements. The Multi-Scale observation sites similar to those deployed for the Wind Forecast Improvement Project (WFIP2) may also have utility for these investigations. This ongoing soil moisture work could have high impacts on improving weather, fire weather, and water forecasts.

- **Snowpack and snowmelt.** The National Water Model lacks a satellite-based snowpack and snowmelt product—important components in water resources management in the country. Assessment and improvement of National Water Model snow data is within reach of PSL scientists. The snowpack and snowmelt work for Maine can be built upon for these activities. This includes assessment of remote sensing-based forcings and their integration into National Water Model. PSL's excellent strength and capabilities in observation, monitoring, and field campaign provides unique opportunities to achieve that.

- **Flash flood forecasting and vulnerability mapping in large urban area.** Urban hydrology, especially flooding, plays an important role in sustainability of our urban societies. Urban flash flooding is becoming more frequent and is a serious problem

affecting cities all over the world, especially those in coastal communities. The latest advances in remote sensing technologies (both satellite based as well as radar, and UAS) can be used to develop such a tool for urban cities. PSL's experience gained in the Maryland project can be built upon to expand and develop an operational urban flash flood alert product (a major National Weather Service [NWS] interest).

1.9. Theme 3: Marine Resources Management

The PSL team presented an impressive list of scientific activities to support marine resource management, including marine ecology, fisheries, boating activities, and energy exploitation—ranging from the tropics to the Arctic around all our national coastlines. PSL scientists have provided substantial new information concerning climate impacts on these resources, developed targeted observational and modeling strategies, and built a firm understanding of many of the important processes involved in their variability and predictability.

Their work in the Pacific sector is enjoying a high-profile impact in the climate, ocean, and marine ecosystem community through their numerous publications, talks at scientific meetings, and service on strategic scientific panels, such as Climate and Ocean-Variability, Predictability, and Change (CLIVAR) and PICES. Their analysis of hindcasts, reanalysis products, and climate simulations of ocean climate conditions along the U.S. West Coast during El Niño and La Niña events beautifully demonstrates the level of probabilistic consistency that we can expect from tropical Pacific El Niño-Southern Oscillation (ENSO) forecasts. These remote events wield local influence in both the surface and subsurface conditions of ocean physics and biogeochemistry, which consequently impact managed species in fundamentally unique ways. PSL led a team of scientists to pioneer the use of multi-model ensembles of climate forecasts in applications relevant to marine ecosystems around our coastlines, such as sea-surface temperature in retrospective forecasting. They are also leading the field in developing statistical forecasting tools for ENSO and other climate phenomena, and then applying them to understanding the limits of predictability as well as the key elements of the physical state that lead to optimal skills levels.

Marine heat waves (MHW) are becoming increasingly common due to global warming, perhaps in conjunction with other intrinsic mechanisms linked to the changing background state. These extreme events can exert considerable stressors on the marine ecosystem. PSL scientists have developed a novel way to link MHW to shifts in habitats associated with harvested fisheries. This could lead to practical use in various management schemes. They also have developed habitat suitability indices based on ocean physical forecasts that can be applied to both protected and exploited highly migratory species. In addition, they have developed statistical forecast tools in attempts to predict MHW, assuming that a recurring process controls their development. These approaches are all timely in that MHWs are often featured in high-profile news reports in the media that are associated with such impacts as deleterious effects on harvested species (such as crabs), die-offs in seabirds, and changes in marine biodiversity.

Climatic change continues to intensify, and PSL scientists are at the forefront of using global climate model future projections in regional downscaling strategies along our coastlines, including the U.S. East Coast. In the Future Seas project, PSL physical scientists worked with NOAA Fisheries experts on ecology to develop sophisticated interactive models that cascade

from climate-change projections to oceanographic environmental changes to biogeochemistry to species-specific regional responses and socio-economic impacts. This novel and exciting approach can yield important information for managers to plan for infrastructure and regulatory needs in the coming decades.

Sea level rise is another threat to U.S. coastlines that PSL scientists are actively studying. They are using their expertise in making predictions to link with other NOAA scientists in generating important sea level outlooks that combine the natural variations from climate events with the long-term trends. Their work also extends into the coastal flooding arena, which combines oceanic forcing from sea level variations with streamflow coming off land from precipitation events. Those factors are then synthetized with wind-wave and hydrodynamic models to render predictions for various parameters of flooding such as timing, peak, and duration. This work is at the vanguard of the science of oceanographic-hydrological interactions.

In the Arctic, PSL has designed and developed over several years the Coupled Arctic Forecast Systems (CAFS). This connection with National Centers for Environmental Prediction (NCEP) and the development of the Unified Forecast System (UFS) has already yielded useful ice forecasts that are highly valued by fishers, endangered species managers, boaters, indigenous peoples, and the Coast Guard. CAFS represents a sterling example of a cross-disciplinary cooperative accomplishment for PSL.

PSLs plans for the future include very encouraging signs of their continued superb performance in using understanding of climate and oceanography to develop tools to predict and protect our coastal environment in the broad goals of NOAA's charge concerning fisheries, marine navigation, energy exploitation, and the stewardship of endangered species on time scales of days, seasons, and decades.

Information is vitally needed by NOAA for proper management, monitoring, and planning strategies for our marine resources. This is particularly relevant to NOAA Fisheries, which manages a large number of fisheries. Understanding how climate, including atmospheric forcing of the ocean and the consequent oceanic environmental response, can impact the oceanic food web and drive possibly predictable components in the ecological response is a promising approach that is being vigorously pursued by PSL.

Much of their applied work is frequently converted into usable products that are readily available through the displays in their web portal. These forecasts and diagnostics can help stakeholders in choosing the best strategies for serving the citizens and societies they represent. Our socio-economic fabric can then become more resilient and sustainable through these PSL efforts to predict and understand the impacts of these climate events in the oceanic, cryospheric, hydrologic, and atmospheric systems along our nation's coastlines.

Several of the PSL scientists serve on high-profile committees for climate and fisheries organizations that link PSL strengths with ecologists through coordination of research activities on physical-ecological interactions.

All signs point to PSL functioning extremely well as a team on multiple levels. These include coordinated efforts to connect physics to biology in the ocean, sharing information and contributing to joint development projects with stakeholders from other government sectors (including within NOAA), and effectively collaborating with scientists at academic institutions and other government laboratories.

The strategy of hiring a scientist who is split-funded 50-50 to directly bridge PSL and NOAA Fisheries is paying huge dividends. This arrangement has catalyzed a large number of research efforts that exploit physical oceanographic and climate process understanding and relate it to the response of the marine ecosystem. We applaud this novel and efficient approach and encourage more of the same in future hiring plans.

1.10. PSL Observing/Field Programs

1.10.1. Observing

PSL has world-class expertise in observing across the land, atmosphere, and ocean using *in-situ* sensors and radars. The security of Federal funding and effective tenure at PSL has allowed Principal Investigators in specific areas to pursue their fields of interest and grow expertise over the years to reach this high level. PSL staff have developed systems to integrate different sensors into effective observatories for surface fluxes, atmospheric rivers, and polar environments. PSL le d the De-Icing Comparison Experiment (D-ICE) study of surface radiometers under icing conditions.

PSL data stewardship gets high marks for archiving and serving different research and climate related data sets. Further work on data stewardship is needed related to adding search-able metadata and using community data formats compatible with open-source visualization tools. The Department of Energy's Atmospheric Radiation Measurements data archive, which includes easy to access perusal plots and information on data quality for each data set, is a good model to emulate. NOAA has been a leader in making data accessible via the cloud, for example, the archive of radar data from WSR-88D network. PSL could consider making some of their data analysis and visualization tools cloud-based to enhance and expand the research community's use of their field project datasets.

Air-sea interaction observations (where Fairall has been a key in developing sensing systems at the air-sea interface) and algorithms for computation of air-sea fluxes as well as Arctic observing are among PSLs areas of world-class expertise. This expertise supports activities in PSL for extremes predictions, water resource management, and marine resource management. Observing expertise was cast in the light of learning more about processes that might not yet be resolved explicitly in models, a future observing system in the Bering Sea, and answering science questions. Being able to accurately observe and work on parameterizations of physics not yet resolved or realistically represented models is a great asset for PSL, NOAA, and the Nation.

Panel members recommend growing in-house interactions of PSL modelers and PSL observers and maximizing benefit from PSL observing capabilities and involvement in process studies to assess and improve models. Synergies between PSL data archiving and serving, PSL's very accurate observing capabilities, and PSL's modeling efforts offer the core of an ongoing capability of assessing model realism, driving model improvement, and motivating field programs.

1.10.2. Field Programs

PSL uses its observing expertise to great advantage and adds to it world class science leadership in its participation a number of field campaigns. PSL staff have been effective leaders and developers of science planning for field campaigns. They have proven to be reliable, dependent partners and colleagues. As a result, PSL is highly respected for its participation in field campaigns, including the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAIC), El Niño Rapid Response, the WInd Forecast Improvement Project, Atlantic Tradewind Ocean-Atmosphere Mesocale Interaction Campaign (ATOMIC), and Lower Atmospheric Profiling Studies at Elevation—a Remotely-piloted Aircraft Team Experiment (LAPSE-RATE) and mention of possible future campaigns. PSL Director use of discretionary funds to help initiate and seed PSL investigators to plan and then participate in field campaigns is recognized and rated highly.

Overall, PSL's field campaign roles and expertise and management's support of engaging in and growing field campaigns is highly rated. The field projects address key science questions in the three themes. PSL is a microcosm of modeling, observing, and field campaigning "under one roof". A recommendation is for PSL to find additional ways to use this synergy to make more effective use of its expertise to improve model realism by feeding back from the field work to assess, and address NOAA operational model shortcomings.

1.11. Modeling and Forecasting

PSL focuses on:

- Working with information gathered in observational campaigns to evaluate forecast systems and process models;
- Investigating key processes in coupled models, including cloud micro-physics and radiative feedback, fluxes, atmospheric boundary layers, and chaotic processes;
- Supporting development of physically based numerical weather-climate prediction algorithms to improve state estimates, reduce errors, and improve the probabilistic predictions within the UFS; and
- Producing experimental forecasts intended to advance process understanding, benchmark operational forecasts, and stakeholder support.

PSL sees modeling and forecasting in the intersection of all of its other interest and focus areas including: research partnerships, observing capabilities, field campaigns tied to predicting extremes, water resources, and marine resources. This is a very appropriate characterization of how modeling use is informed by data collection and is a high-value approach to improve our understanding of processes that can lead to improved predictions.

PSL modeling research has informed and improved a number of models in NOAA. One area that PSL has promoted in a number of research areas and topics is the use of stochastic parameterizations within NOAA operational models of UFS and Global Ensemble Forecast System version 12 (GFSv12). Additionally, PSL presented a number of successful new or

improved algorithms developed in direct cooperation with other NOAA offices including Geophysical Fluid Dynamics Laboratory (GFDL) and the National Water Model that have quantifiably improved NOAA operational models.

The understanding from PSL's modeling diagnostic efforts for tropical moisture dynamics has a direct impact on current and upcoming UFS and Global Forecast System (GFS) versions. Modeling evaluation efforts were also tied to flood events, drought events, Arctic events, amongst other practical applications. PSL also identified the tie between the modeling and forecasting efforts with the observational campaigns. In particular, the El Niño Rapid Response (ENRR), ATOMIC, and MOSAIC efforts and feedback mechanisms by which observational campaigns inform modeling efforts—and modeling efforts help define the questions of ENRR, ATOMIC, and MOSAIC in real time.

PSL scientists are recognized internationally as leaders in the field for many aspects of modeling, including statistical inverse modeling, data assimilation strategies (especially in the ensemble Kalman Filter framework), stochastic parametrizations, surface flux algorithms, cloud-microphysics-radiative interactions, model diagnostic evaluations, and experimental predictions. Overall, the broad, deep, and practical approach that connects with observational efforts and projects strongly onto real-world applications and stakeholders is tremendously impressive.

PSL could benefit from a more structured or defined interaction between PSL modeling efforts and the predictions systems that their science could improve. For example, the National Water Model was identified multiple times as an area of interest to PSL scientists—yet it appeared that there were some miscommunications or further opportunities for better coordination between PSL and the National Water Model. Some direct linkages identified between PSL and UFS development include, but are not limited to, detailed employees and other informal and formal coordination activities. A few success stories identified where PSL modeling outcomes were incorporated into operational NOAA models, including UFS, GFSv12, and other models. That type of outcome should be the goal for many PSL modeling activities. To achieve that, PSL should look for greater structured and formal relationships with operational modeling and prediction programs throughout NOAA. Those programs should help PSL define priorities for modeling research, as feedback from PSL identified the need for more opportunities for direct involvement in NOAA's operational programs.

PSL also uses stochastic parameterization schemes to reduce error characteristics in prediction models. Adding stochastic elements to climate forecast models is a recent development that shows great promise in enhancing skill levels and better quantifying uncertainty estimates in forecasting. It is commendable for PSL to be leading innovative efforts in these types of parameterizations that improve forecasts. At the same time, we hope that PSL does not focus solely on stochastic parameterizations and continues to explore the root underlying physical processes. Modeling events that are of low probability of occurrence may be "better" portrayed through stochastics now, especially in risk assessment of extreme events. However, ultimately a better understanding of the physics will help NOAA predict phenomena more accurately into the future.

PSL's modeling focus on applications and particularly emphasizing the real-world impact of these focuses, such as droughts, floods, and reservoir management is not only commendable but

also shows that PSL scientists are seeing the forest through the trees as modeling efforts are defined.

Overall, the work is of extremely high quality and of great value to NOAA and the entire climate modeling community. The work is highly relevant—although improving internal NOAA coordination (which we sympathize can be sometimes challenging due to programmatic inflexibilities) would make it more so. PSL is also performing at a high standard, although exploring how to measure or quantify performance would benefit some internal checks and balances such that performance can be evaluated at a variety of levels within PSL from individual scientists, to teams, to the organization as a whole. This performance should evaluate more than just peer-reviewed journal articles.

1.12. Research Partnerships

PSL works with a wide range of groups in a similarly wide range of capacities to develop and transition research advances into NOAA services and information products for use-inspired research. Through partnerships, PSL gains insights into what key decisions are being made from its research, which in turn further influences and shapes research directions and refines products produced by PSL. This includes partnerships across NOAA, such as work with the Environmental Modeling Center (EMC), to improve ensemble S2S prediction systems and bias-correct and calibrate operational ensemble predictions. PSL is a key partner with the Climate Prediction Center (CPC) in providing the algorithmic advances that help produce more accurate forecasts to help them serve a variety of S2S customers. These also include partnerships in other Federal agencies, academia, and in the private sector. Key partnerships, for example, those highlighted in the new draft strategic plan, extend across other parts of the Federal government such as water and weather work with the Bureau of Reclamation, as well as with several state and regional agencies such as the CaDWR.

Meetings with and letters from stakeholders indicated that partnerships with PSL were highly valued. In general, stakeholders view PSL as a trusted resource for high quality scientific contributions, and that there is an overall culture of openness and responsiveness to partner needs.

While there is no doubt these collaborations and partnerships are valuable and have been productive, there were a number of questions about how well these partnerships have actually advanced PSL's capabilities and its ability to fulfil its mission. Also, a key question is should, and if so how, can PSL strengthen and promote true partnerships rather than collaborations? Throughout the review, it often appeared that PSL interprets partnerships and collaborations interchangeably. While collaborations emerge in an organic and ad hoc fashion at the PSL staff level, partnerships would represent more formal and strategic connections to other parts of NOAA, organizations, centers, labs, professional societies, and government entities—and would be most appropriately identified by upper management's strategic considerations and planning. PSL would likely be better served by a more strategic approach to prioritizing partnerships that starts with executive-level deliberations, leadership, and strategic planning, including metrics to evaluate partnerships. PSL leadership should also seek partnership opportunities to combine resources where appropriate—both domestically and internationally in order to realize efficiencies in the face of current and likely continued fiscal pressures.

1.13. Transfer Opportunities (R2X / R2O)

Transferring research project outcomes to operations, applications, and services (for example to decision makers) is one of NOAA and PSL's essential goals. This is necessary to ensure the most advanced science is being provided to support NOAA's mission. This is essential in both R2X as a whole and Research to Operations (R2O) in particular. R2O is the process by which a research project led by an investigator, in providing added value, is systematically transitioned to a NOAA operational unit. It allows NOAA to maximize the return on investment of its research and remain competitive and at the edge of science and its products. PSL works with NOAA enterprises and line offices including Federal, State, and local agencies external to NOAA to expedite the timely transfer of research findings into operational environments for use in forecasting, decision making, planning, and even policy.

PSL research is mostly focused on transitioning its research to applications and operations within NOAA and external to NOAA. The major contribution of PSL research is often an early and essential link in the chain of transition to operations, services with focus on end users and stakeholders. PSL contributions are categorized in three categories:

- model improvements;
- experimental predictions and guidance; and
- forecasts and projections, especially in ocean environments.

It is fair to indicate that PSL has achieved major accomplishment in each category. Review panel members' findings include:

- **Model improvement:** Examples include improvement in forecasts by NWS NCEP which are used by NOAA Weather and River Forecasting Centers in water management, emergency management—and Weather Forecast Office's flood statements which ultimately save lives and properties. PSL has been able to transition model diagnostics with special improvements into operational models, including UFS, High-Resolution Rapid Refresh (HRRR), GFS, and recently even the National Water Model. Other examples of improvements to NWS operations include: WFIP2, 20th Century Reanalysis (20CRv3), and AQPI.

- **Experimental predictions and guidance:** PSL works on drought research and product development. Examples include: National Environmental Satellite, Data, and Information Service (NESDIS)/US Drought Monitor/Outlook which helps with drought preparedness and mitigation efforts and FEWS NET which assists with food security abroad. Both of these will help in emergency management. Some of these outcomes may be provided directly to users and stakeholders. In enhancing NOAA's forecast capabilities, PSL provides sub-seasonal to seasonal (S2S) forecasting, Evaporating Demand Drought Index, and Air Quality Forecasting for PM2.5 and Ozone.

- **Forecasts and projections in ocean environments**: PSL has been involved heavily in knowledge transfer, especially when it comes to synthesis and assessments of science based weather, water, and climate knowledge for NOAA science and stewardships. Examples include Climate Change Web Portal, informing NOAA Fisheries about future impacts to marine resources, vulnerabilities to changing climate, and ultimately the interface between fisheries and water management. PSL scientists collaborate with NOAA Fishery scientists to incorporate climate and ocean model to produce outputs which can be used in evaluations for management strategies on marine resources such as lobsters, cod, sardines, swordfish, and other species. At the national level, they participate in NMFS vulnerability assessment and scenario planning for marine species and habitats. They also participate on Integrated Ecosystem Assessment Program and Habitat blueprint.

PSL scientists are engaged in many other cross disciplinary R2X activities. Examples in this broader category include:

- Model improvements;
- Enhancing NOAA products and services (such as the National Water Model, HRRR, Global Ensemble Forecast System [GEFS], etc);
- Analysis tools and datasets (such as Arctic Diagnostic toolkit, Web-based Reanalysis Intercomparison Tool [WRIT], and Climate Model Visualization and Analysis Tool (FACility for Weather and Climate AssessmenTS [FACTS]);
- Instruments, such as using UAS for soil moisture, snow level radar, ocean surface wave radar;
- New products and services, which include CAFS and Arctic sea ice forecasting and monitoring system; and
- Knowledge exchange and use, which include ongoing work with the National Ocean Service (NOS), NOAA Fisheries, U.S. Army Corps of Engineers (USACE), and the Bureau of Reclamation for interpreting climate conditions.

PSL scientists have developed an excellent strategy in transitioning their research into applications. They developed good partnerships with a large number of stakeholders, most of these partnerships are aimed at transitions. Their participation in many formal and informal testbeds have proven to be the key to building these partnerships. PSL scientists actively participate in many workshops, typically with operational end users and stakeholders. Examples include co-hosting the 2015 NWS Climate Diagnostics and Prediction Workshop, hosting annual Fisheries Integrated Ecosystem Assessment Workshop in Boulder, and participating in NWS Climate Predication Assessment Workshops. PSL also encourages their scientists to recruit people interested in user-inspired work, such as hosting three Postdocs Applying Climate Expertise (PACE) fellows.

In summary, PSL scientists use different approaches to understand basic applied sciences in responding to NOAA operational and other stakeholders' needs. While NOAA is a priority, PSL scientists focus on responding to their stakeholders needs, which might not be the same as NOAA's direct needs. While differing priorities can be a challenging issue, this can also be a unique opportunity to build and expand relations between NOAA and stakeholders. PSL is in a unique position to address user-inspired research strategy. To strike a balance between responding to end user needs now and anticipating and providing solutions with innovative research for future user needs with meeting NOAA's operational needs, PSL has to recognize that it is a NOAA entity—and PSL needs to focus more on NOAA's operational needs.

As a laboratory with many excellent capacities in modeling, forecasting, and observations, at both national and international levels and connections, PSL can conduct field campaigns in many part of the United States and the world, including marine and polar environments. This unique strength should also be directed to develop of R2O products for NOAA's line offices. Most of R2X activities of PSL can be categorized as research for applications and services. Extra effort to emphasize R2O in NOAA would certainly benefit the PSL. R2O opportunities exist in National Water Center; NESDIS' Center for Satellite Applications and Research (STAR), and NWS to mention a few. While using satellites to produce data is evident in PSL science, PSL scientists could be more engaged to be effective in producing R2X and even R2O in satellite data application and products development. In addition, PSL needs to develop metrics and identify methods to assess success in R2X.

1.14. PSL/Cooperative Institute Interactions

The two Cooperative Institutes, Cooperative Institute for Research in Environmental Sciences at the University of Colorado, Boulder (CIRES) and Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins (CIRA), are invaluable resources for PSL. With finite and well-defined annual funding through OAR, PSL base funds can support a limited number of Federal employees. CIRES and CIRA provide the means for additional soft money supported staff to work at PSL. CIRES and CIRA also provide interfaces to two university communities. CIRA has expertise in radar technology and remote sensing, including operating an Earth Station for Geostationary Operational Environmental Satellites (GOES) and archiving GOES and other satellite data. Work at CIRA involves modeling and data fusion as well as tests and verification for satellite sensors. CIRES has more than 800 employees and expertise in weather and climate, changes at Earth's poles, air quality and atmospheric chemistry, water resources, and solid Earth sciences.

Without doubt, the two CIs allow PSL to draw from a large pool of talented researchers without having to commit Federal support and also allow PSL to interface to the more diverse research portfolios of two universities.

Panelists recommend sustaining the partnership between PSL and the CIs. At the same time discussions with early career staff at these institutions prompt these recommendations:

- **Communications.** Improved clarity in communication about CI staff transitions to Federal career paths would be helpful. This could include posting and making readily available information (e.g., in the last 5 years, eight Federal positions, including X Scientist I and Y Engineer I positions were filled at PSL positions posted through

USAJobs). Transition from CI to Federal staff occurs for a subset employees—but it is only handful of people and often takes years. The vast majority of CI staff working on PSL projects will not have the opportunity to transition to Federal positions. A number of PSL staff we heard from indicated that they had spent several years and more as CI employees before transitioning to Federal employment at PSL. As such, they lived with the uncertainty associated with soft money support before obtaining the effective tenure of Federal employment.

- **Chains of command.** In addition, staff working together operate under different supervisory and human resources oversight chains of command. The requirement to have a Federal employee communicate a CI scientist's ideas upwards within NOAA yields asymmetrical power relationships. A particular concern is resolving problems and taking corrective actions when the parties work for different organizations (e.g., a group leader who engages in inappropriate behavior towards a junior staff member from a different group). PSL has been proactive in ending some CI staff's supervision of support staff.

Overall, the functioning of the CIs in support of PSL is a very positive situation for PSL. It allows staffing up in areas beyond the limitations of its Federal base budget. It engages students and staff and the diversity of two universities. An ongoing and active dialog between PSL management, including human resources, and CI management also including their universities' human management, is recommended to coordinate staff training in appropriate and ethical behavior and develop means to respond to negative interactions between PSL and CI staff. At the same time, that dialog is needed to maintain alignment of PSL's core research activities and the themes and staffing that the CIs carry forward in their 5-year cycle of umbrella proposals to NOAA.

1.15. PSL Structure/Operations

Embedding PSL science staff for a detail within other branches of NOAA and other agencies on either a temporary or ongoing basis has been effective in improving and deepening working relationships. Overall, there is a sense from both PSL and stakeholders that groups within NOAA are working together better now than they were 5 years ago. **However, the Review Panel found multiple instances where coordination among NOAA groups still needs improvement—particularly between operational centers running models and groups like PSL that are working on evaluating and refining parameterizations for those models.** PSL's work is hampered by lack of access to clear documentation and the latest code base for several of NOAA's operational models. For example, PSL is not always "in the loop" on version changes to the National Water Model—which is a hurdle in evaluating the model. As a result, retrospective runs for PSL's analyses do not often match the model's operational configuration.

While it is important for research from NOAA labs to transition to operations, the current OAR and NWS imperative for most activities they sponsor to have a transition plan has an unintended consequences emphasizing "safe bets" and hence stifling risk taking, creativity, and innovation. A stakeholder mentioned that OAR is creating unreasonable pressure on labs to pick and choose wisely so they can count transitions on a metric chart. One of the stakeholders mentioned that if a new product does not get to Technology Readiness Level 9 (System Fully

Operationally Integrated), then it is considered to be a failure. A rebalance of priorities from OAR that explicitly includes funding for science that is exploratory rather than intended for operational transition will yield important learning that will enhance the research enterprise. Scientists are most innovative when it is safe to fail.

The members of the panel value the position of a chief scientist supporting PSL. During presentations the duties and all the activities of the chief scientist were not discussed, and the panel thinks there is value in a more robust presentation of this role in future reviews. The panel sees considerable value in the chief scientist working with the PSL Director in setting scientific priorities and coordinating activities across thematic areas of the Lab. There is also a lot of value with a chief scientist being a public voice for PSL science, and translating the science being done in a way that is synthesized and summarized for appropriate audiences. Other valuable roles for a chief scientist are coordination with other parts of NOAA, and external, and strategic partnerships that advance the NOAA mission.

3. Culture/Diversity

The review panel commends PSL for identifying that a critical aspect to lab success is employee development and for fostering the development of new employees to become leaders in the future. As such, the panel had the opportunity to meet with the newer staff in a closed meeting on the last day of the review. In the online environment, the panel identified a couple of open questions with the intent to elicit an open dialogue amongst the staff members present. Each PSL/CIRES employee had the opportunity to present their views and experiences with PSL to date. The discussion largely focused on the demoralizing impacts of the behavior of a small number of researchers within the lab, including bullying behavior toward some scientists and visitors. This is a topic that each member of the review panel feels strongly about and should be addressed separately within this report.

Some employees identified bullying as being manifested as unprofessional behavior, not respecting different points of view, meeting new ideas with condescension and disrespect, and a small number of supervisors bad-mouthing their staff to other staff in their presence. Seminars were described as sometimes being combative, and some employees felt that some speakers were—in effect—attacked by other PSL scientists. These kinds of problems also happen in field work and were not limited to onsite within the physical laboratory in Boulder. The staff were disturbed that no bystander steps in to stop these incidents when they occur. Inaction is viewed by some as being complicit in the bad behavior. The employees knew of people who left PSL because of the culture and felt that this problem is negatively impacting diversity and retention. Staff felt that current training on these issues is more "tick the box" and is not effective.

These types of problems are vexing for management as even a few employees practicing such behavior have a disproportionate influence on degrading the environment for all. Each member of the review panel agrees that this is a significant issue that must be addressed, while recognizing management has taken some positive steps in recent years. There appears to be a systemic cultural problem that should be addressed within PSL and CIRES with respect to interactions amongst employees.

In a follow up conversation with PSL leadership, these issues were acknowledged as being real and ongoing. PSL leadership identified for the review panel a number of steps that PSL has already begun to employ to help respond to the cultural issues. PSL has an existing Workplace Advisory Committee that meets several times a year. This committee could be further empowered to enhance a culture of inclusion at the lab, and serve as a mechanism where top-down and bottom-up efforts could meet to advance this goal. Individual personnel discussions with problem employees were also identified as well as working with the Human Resources department. The review panel commends PSL leadership for both acknowledging the issue as well as taking actions to improve the situation and identifies some additional opportunities as it is clear that additional actions are required.

The review panel promotes an all-inclusive approach to improving workplace culture through a variety of activities from increased training, clear guidance and accountability, and increased interactions with human resources to address and take action when problems continue to arise.

There are a variety of training opportunities intended to improve workplace culture. One example are courses focused on "Civil Treatment" in the workplace for both employees and managers. Additionally, high quality bystander training such as that offered by the National Science Foundation's (NSF) ADVANCEGEO may empower bystanders to step in and change the cultural norms by not tolerating bad behavior in real time. More readily visible consequences for bad behavior within Human Resources guidelines are needed to demonstrate that such behavior is not acceptable. While each incident has unique aspects, having a set of procedures to address these incidents agreed on ahead of time between PSL and CI's Human Resources and management would help. One additional aspect and complexity that came to light during these conversations is the different and separate management structures at PSL and CIRES that issues of a human resources nature and cultural nature are reported to. While this review panel does not have a formal approach to propose to address this issue, each member thinks that PSL leadership and CIRES leadership need to come to an agreement on an approach to dealing with this issue and have a uniform, consistent, and transparent approach that can be continuously communicated and understood with all employees—regardless of whether they are employed directly by PSL or CIRES.