NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Earth System Research Laboratory

Physical Sciences Division Strategic Plan 2016–2020

Contents

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Executive Summary

The Physical Sciences Division (PSD) supports NOAA and national needs for actionable science-based information through research that advances physical understanding and predictions of Earth's atmosphere, oceans, land, cryosphere, and their interactions. PSD works with partners to transition research advances into NOAA services and information products to support public and decision-maker needs. PSD research addresses critical science gaps in current NOAA services, and also conducts research that anticipates new capabilities that will be required to meet emerging challenges for NOAA and the nation.

To achieve the most rapid and effective progress, PSD's strategy builds from its outstanding capabilities in developing and applying problem-focused observations, its core scientific expertise in physical processes, phenomena, predictability and predictions, and its extensive partnerships within NOAA and externally. Core capabilities extend from seconds to centuries, providing PSD with unique strengths to conduct research that seamlessly extends over the continuum of weather and climate. Understanding the connections between weather and climate is central to addressing major challenges to NOAA and society, such as anticipating how extreme weather events and their impacts will be affected by climate variations and change. PSD research also extends from global to regional and local scales, enabling a more comprehensive physical understanding of multiscale processes and interactions and their scientific and practical implications.

Extensive capabilities in observing, understanding, modeling, and research-to-application transitions enable PSD to conceive and contribute to the development of integrated environmental information systems that will be required to meet current and anticipated future NOAA and national needs. Coordinated research on specific regional problems provides rich opportunities to accelerate science advances while also assessing user needs and the applications and value of new science-based information. Innovative partnerships and focused and sustained engagements with users and stakeholders will continue to support a broad range of scientific and practical applications, as well as inspire new PSD research directions.

Between now and 2020, PSD will continue its core research to improve physical understanding and predictions of Earth system processes from the tropics to the poles and from global-to-local scales to support NOAA and national needs. PSD will focus particular attention on key challenges to NOAA and the nation in three areas where PSD has established scientific expertise: extreme events, water, and the Arctic environment. To achieve most rapid progress, PSD will work together with partners to address two overarching science goals and three priority research goals:

Overarching Science Goals

1. Develop new knowledge and capabilities to explain observed weather and climate extremes, variations, trends, and their impacts to inform risk management and adaptation decisions.

2. Identify new sources of predictive skill and improve predictions of weather, water, and climate through observations, understanding and modeling of physical processes and phenomena of the coupled Earth system.

Priority Research Goals

1. Rigorously characterize and predict weather, water, and climate extremes and their uncertainties to inform decision-making.

2. Develop new process understanding, observing, and modeling capabilities to predict conditions associated with too much or too little water for early warning, preparedness, resource management, and adaptation.

3. Increase process understanding of the coupled Arctic system and Arctic-lower latitude interactions to improve NOAA weather, climate, and sea ice forecasts.

For all goals, PSD will develop and transition research advances into NOAA services and information products.

Introduction

PSD provides NOAA and the nation with sustained and committed expertise in physical sciences research that bridges weather and climate.

The foundation of NOAA is science. The Physical Sciences Division (PSD) meets critical NOAA and national needs for actionable science-based information on the Earth's changing environment. PSD provides NOAA with sustained and committed expertise in physical sciences research that is required to meet NOAA's evolving mission requirements for observations, process understanding, and predictions of the Earth's atmosphere, oceans, land surface, and cryosphere. While NOAA's foundation is science, at its heart is service. Because of this, PSD research focuses specifically on addressing critical science gaps identified by current services, and also on conducting innovative research that anticipates new environmental information and services that will be required in the future by NOAA and the nation.

This strategic plan describes the research strategy for the PSD for the five-year period from FY2016 to FY2020. The strategy builds from PSD's FY2011–15 plan and scientific progress achieved over that period. It supports the missions of NOAA, the Office of Oceanic and Atmospheric Research (OAR), and the Earth System Research Laboratory (ESRL). The strategy is developed within the context of broader societal drivers, national and international science priorities, and emerging opportunities to accelerate scientific progress. These key drivers provide the basis for defining research goals for PSD to address NOAA and national needs. PSD's research goals also provide a framework for integrating capabilities across PSD to achieve the most rapid and effective scientific progress.

Within NOAA, PSD conducts focused physical sciences research that bridges weather and climate. Understanding the connections between weather and climate is vital to addressing questions of great societal interest, such as how extreme weather events and their impacts are being affected now, and are likely to be affected in the future, by climate variations and change. PSD's exceptional strengths in observing and

PSD has unique strengths for addressing key challenges to NOAA's water services...and in translating research advances into water information products and services.

understanding physical processes and phenomena underpin science-based explanations for the causes for observed weather and climate conditions, and for developing NOAA predictions that extend seamlessly from weather to climate. Crosscutting capabilities from observations to experimental services provide a foundation for developing, prototyping, and improving NOAA products and services in mission-critical areas of climate, weather, and water. These are vital for improving Earth system models and predictions, including addressing frontier science challenges of the coupling of Earth system components across the atmosphere, oceans, land, and cryosphere.

In addition to weather and climate science, PSD has unique strengths for addressing key challenges to NOAA's water services in observations, process understanding, modeling, and predictions of the water cycle, and in translating research advances into water information products and services. This allows PSD to conceive and contribute to the development of integrated water information systems that will meet NOAA and national needs for actionable science-based information to anticipate, prepare for, and manage water-related risks and opportunities. To achieve maximum value for NOAA and the nation, PSD also works with partners to translate scientific understanding and predictions of the physical system into information that can be used to manage and conserve coastal and marine ecosystems and resources, for which NOAA has primary mission responsibilities.

The next two sections summarize the foundations for PSD's strategy. Section 2 provides a brief overview of PSD's mission, science capabilities, and partnerships. Section 3 discusses primary drivers, emerging trends, and research opportunities that inform PSD's strategic research directions. Section 4 then defines five major research goals for PSD for 2016-2020, together with key science questions, objectives, and indicators for success for each goal.

PSD Science Overview

Mission

PSD supports the missions of NOAA, OAR, and ESRL. NOAA's mission is summarized as Science, Service, and Stewardship: "To understand and predict change in climate, weather, oceans, and coasts; to share that knowledge and information with others; and to conserve and manage coastal and marine ecosystems and resources." Within NOAA, OAR's role is "To conduct environmental research, provide scientific information and research leadership, and transfer research into products and services to help NOAA meet the evolving economic, social, and environmental needs of the nation." ESRL's mission is "To observe, understand and predict the Earth system through research that advances NOAA's environmental information and services from minutes to millennia on global-to-local scales." Within ESRL, PSD's mission is "To support NOAA and the nation through physical sciences research that advances understanding and predictions of weather, water, and climate, and translates the research findings into actionable information and services."

Science Capabilities

PSD has long-standing capabilities in the development and use of problem-focused observations. Its core scientific expertise is physical sciences research that focuses on processes, phenomena, predictability and predictions. PSD's science capabilities are greatly augmented by extensive partnerships within NOAA and externally. These partnerships are vital to advancing scientific knowledge and to developing new products and services for societal benefit. Core capabilities extend from seconds to centuries, providing PSD with unique strengths to conduct research seamlessly from weather to climate. This section briefly describes each capability.

PSD observation-based research provides the core capability required to identify and quantify the roles of various physical processes in the Earth System.

Problem-focused observations are central to the observational process research conducted at PSD. They provide the core capability required to identify and quantify the roles of various physical processes in the Earth system, often in harsh and challenging conditions. PSD's observational activities have three critical facets: development, applications, and synthesis. To address a specific science problem, PSD scientists and engineers develop, test, and apply innovative measurement techniques and observational platforms. A primary application of the observations is to improve understanding of key physical processes. Specific observational platforms and measurements are problem-dependent, and may be deployed on land, sea, ice, or in the air in process studies and field experiments in which NOAA is participating. PSD also conducts long-term observations in the Arctic to better understand Arctic processes and monitor climate change, along the Pacific coast to better monitor and understand Atmospheric Rivers and related processes that lead to extreme precipitation and flooding events, and across the world's ocean to better understand and characterize air-sea fluxes. In addition to direct observations and measurements, PSD scientists develop and apply methods to assimilate observations within models to create objective, quantitative representations of past atmospheric conditions, or atmospheric reanalyses, that now extend back well over a century. This work continues to open opportunities for a vast range of new research and applications.

PSD's expertise in physical processes research extends from global-to-local scales...and from the ocean to the stratosphere.

Processes research focuses on understanding and quantitatively representing fundamental processes that determine temporal changes of Earth system components - the atmosphere, ocean, land surface, and cryosphere – as well as their interactions. Physical processes are usually represented explicitly or implicitly in prediction models by specific terms in model equations. Advances in process understanding and modeling are therefore critical to improving NOAA models used for weather, water, and climate forecasts. PSD scientists are world leaders in physical processes research. They provide vital contributions to observational and process studies in regional field campaigns conducted over many regions of the globe, from the deep tropics to the poles. Process expertise spans all of PSD's research teams, with strong foci in specific areas. Specific teams are focused on observations and processes for the coupled ocean-atmosphere system, the atmospheric boundary layer, water cycle, and polar region, but expertise extends over other vitally important processes in atmospheric dynamics, clouds, radiation, and their interactions. In addition, PSD translates advances in process understanding into operational model improvements. PSD expertise in physical processes research, including measurements, observations, theory, and modeling, extends from global-to-local scales and from the ocean to the stratosphere. PSD's breadth of research capabilities related to physical processes may be unmatched anywhere.

Phenomena are emergent behaviors of the Earth system. They result from interactions among physical processes as, for example, for the El Niño-Southern Oscillation in response to coupled ocean-atmosphere interactions over the tropical Indo-Pacific

PSD's predictions research creates, develops, and tests methods for improving the skill of models and forecasts.

region. Phenomena often convey predictability far beyond what might be anticipated from individual processes alone. PSD scientists have made major contributions toward characterizing and understanding phenomena across weather and climate including: Atmospheric Rivers on time scales of days to weeks; the Madden-Julian Oscillation and organized tropical convection over weeks to a season; El Niño-Southern Oscillation and tropically-forced teleconnections over seasons to years; and modes of climate variability like the Pacific Decadal Oscillation over many years to decades. PSD also conducts research to understand and quantify how phenomena from climate change to synoptic weather variability alter the probabilities and magnitudes of extreme events, in order to provide science-based explanations on the causes for observed extremes and determine how such events might be better predicted in the future. Such work also informs assessments of the needs and suitability of models for predicting and projecting future changes in such events.

Predictability research provides quantitative estimates of the possible predictive skill achievable for a given prediction problem. This potential predictability can be compared with current prediction skill, with large differences between the two identifying gaps where significant predictive advances are possible. Predictability research can lead to new knowledge of untapped sources of predictability and identify priority areas for forecast improvements, informing research directions and resource allocation decisions. Important sources of predictability for PSD research include organized tropical convection, stratosphere-troposphere interactions, atmosphere-land surface interactions, and coupled ocean-atmosphere processes. PSD expertise in this area extends from short-range weather and water forecasts out to decadal time scales, with weather predictability assessments at finer resolution (down to ~1 km) while climate assessments focus on regional scales. This breadth enables a more comprehensive physical understanding of multiscale processes and interactions, and their scientific and practical implications.

Predictions research at PSD creates, develops, and tests methods for improving the skill of models and forecasts. A major emphasis is working in partnership with NOAA NWS to transition PSD research advances into models and algorithms that improve weather, water, and climate forecasts. PSD has world-class expertise in critically important areas such as data assimilation, numerical methods, empirical dynamical modeling, ensemble prediction methods, statistical post-processing methods, and model physical parameterizations. New research in PSD will provide a foundation for eventual implementation of stochastic parameterizations in NOAA models.

Partnerships

Partnerships are critical to PSD's success. They are central to successful transitions from research to operations, applications, or for other purposes (R2X). At the same time, partnerships and user interactions help to identify key science questions and needs that

PSD's innovative partnerships support a broad range of scientific and practical applications and inspire new directions for our physical sciences research.

inform PSD's future research directions (X2R). PSD has extensive partnerships from local to global levels, and from research to services and applications.

Within ESRL, PSD partners with all Divisions on observations and processes research, and in the case of GSD, model development. PSD also partners across OAR labs, such as GFDL, on problems on crosscutting interest. Strong partnerships are critical to transition research to services, for example, through test beds, and to develop and transfer new modeling and predictive capabilities to the NWS. PSD scientists are also working with NMFS scientists to determine climate change impacts on marine ecosystems to inform resource management decisions.

PSD's partnerships with water management agencies, such as the Bureau of Reclamation and the California Department of Water Resources, have helped to realize the value of PSD's research for informing decision-making, while also helping PSD scientists to identify critical research needs. PSD has contributed strongly to national partnerships through contributions to the National Integrated Drought Information System, USGCRP and Interagency Arctic Research Policy Committee (IARPC), and international partnerships through the Intergovernmental Panel on Climate Change (IPCC), the World Meteorological Organization (WMO) World Weather Research Programme (WWRP) and World Climate Research Programme (WCRP), and the Famine Early Warning System (FEWS) network.

Partnerships with universities and centers, NOAA services and stakeholders on specific regional problems, such as through hydrometeorology testbeds (HMTs) have provided rich opportunities to accelerate science advances while also assessing user needs and realizing the value of science-based information. Collaborations have been particularly deep and strong with the University of Colorado/CIRES through projects such as the Western Water Assessment. Innovative partnerships and focused engagements with users and stakeholders support a broad range of scientific and practical applications, as well as inspire new directions for PSD's physical sciences research.

PSD also participates actively in major international research programs and experiments. Field programs extend from studies of the dynamics of the Madden-Julian Oscillation in the tropics to Arctic sea ice. Partnerships can be extensive and diverse. For example, one of the most important contributions of PSD in recent years, the development of atmospheric and oceanic reanalyses that now extend back well over a century, involved national collaborations between NOAA, CIRES, NCAR, Texas A&M University, NSF, and the DOE, tens of thousands of citizen scientists, universities and national meteorological services throughout the world, and organizations such as the WCRP, the Atmospheric Circulation Reconstructions over the Earth initiative, and the Global Climate Observing System Programme.

Strategic Drivers and Opportunities

PSD conducts purposeful, use-inspired research to support NOAA in its mission to meet evolving national needs.

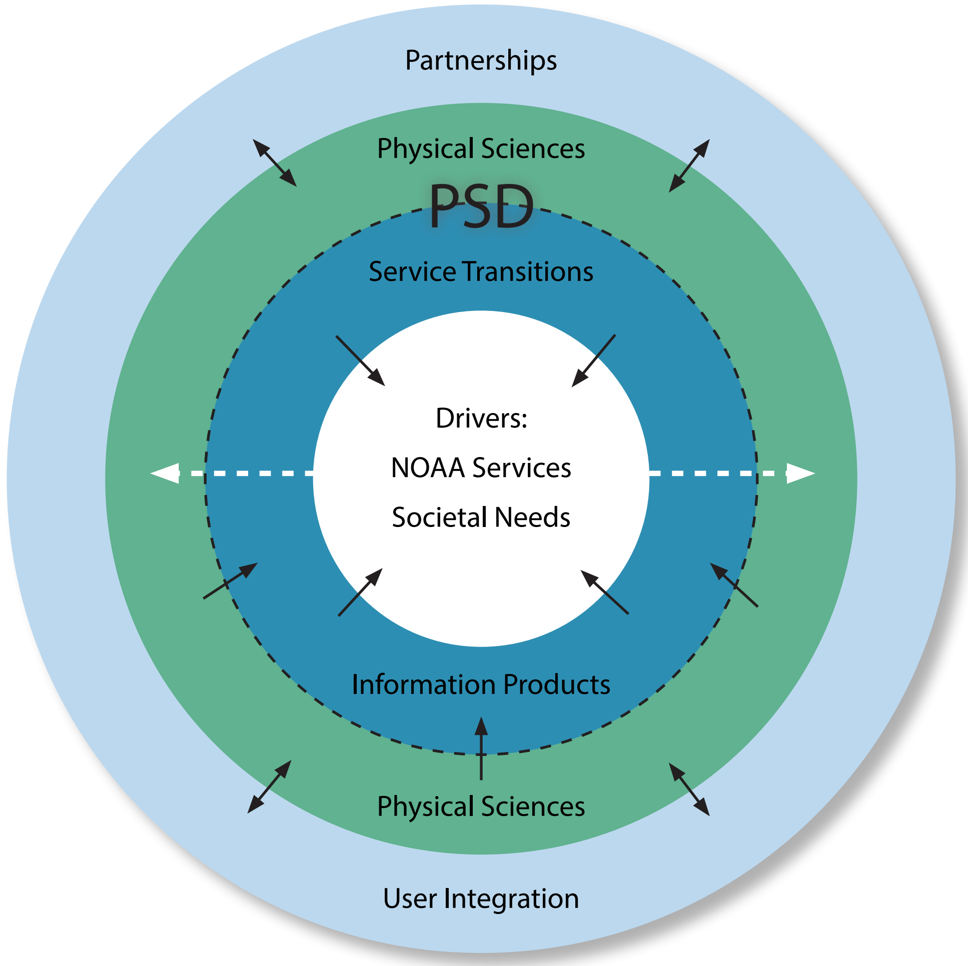
PSD conducts purposeful, use-inspired research to support NOAA in its mission to meet evolving national needs. This approach has been, and will continue to be, at the heart of PSD's research strategy. PSD research contributes to the basic science that is the bedrock for NOAA's services. Perhaps less appreciated, but also vitally important, is research that builds the connections between scientific findings and the services that NOAA provides. PSD research strongly emphasizes such science-service connections. Two other research attributes required to develop more effective NOAA services are responsiveness – understanding current service and stakeholder needs – and innovation – anticipating future needs, including for products and services that may not yet exist. To optimize the value of PSD's research, PSD seeks to achieve an appropriate balance between these two elements, that is, between "user pull" and "research push".

Overview of Strategic Considerations

Figure 1 illustrates core considerations for PSD strategic planning that will be discussed in more detail in this section. At the center are the primary drivers for PSD's research: NOAA's mission and societal needs. PSD's responsibilities are to conduct physical sciences research necessary to address those needs and to translate the research advances into improved NOAA services and information products. External partnerships and user interactions also play an essential role in PSD's research and development strategy. Such partnerships greatly accelerate research progress over what PSD might achieve alone. They also inspire PSD's research in directions that can more effectively serve stakeholder needs and lead to new NOAA products and services. These components are discussed below.

Figure 1

Core considerations for PSD strategic planning.



Drivers

NOAA'S GOALS AND SERVICES

The Next Generation Strategic Plan (NGSP) defines NOAA's long-term goals for Climate, Weather, Oceans, and Coasts. While PSD research contributes to all of these goals, PSD's primary contributions are to the NOAA Climate and Weather goals. Climate and Weather objectives to which PSD's research contributes most strongly are:

- Improved scientific understanding of the changing climate system and its impacts.
- Assessments of current and future states of the climate system that identify potential impacts and inform science, service and stewardship decisions.
- Reduced loss of life, property, and disruption from high-impact events.
- Improved freshwater resource management.
- Integrated services meeting the evolving demands of regional stakeholders.

The strategic plan also provides an overarching, long-term scientific and technical challenge to the agency: To develop and apply holistic, integrated Earth system approaches to understand the processes that connect changes in the atmosphere, ocean, space, land surface, and cryosphere with ecosystems, organisms, and humans over different scales. PSD's role and contributions toward addressing this holistic grand challenge also underpins PSD's long-term strategy.

Following the NGSP, NOAA developed a Five-Year Research and Development Plan for NOAA's R&D activities from 2013–2017, a period partly overlapping with this Plan. The R&D Plan and OAR Strategic Plan identify key science questions for NOAA's strategic goals. PSD research has been aimed at addressing specific questions, many of which will continue to influence PSD's strategy through 2020. Questions of most immediate relevance include:

- What is the state of the climate system and how is it evolving?
- What causes climate variability and change on global-to-regional scales?
- What improvements in global and regional climate predictions are possible?
- How can NOAA best inform and support the nation's efforts to adapt to the impacts of climate variability and change?
- How can we improve forecasts, warnings, and decision support for high-impact weather events?
- How does climate affect seasonal weather and extreme weather events?
- How can we improve forecasts for freshwater resource management?
- How do environmental changes affect marine and coastal ecosystems?
- How can emerging technologies improve ecosystem-based management?
- What are the best observing systems to meet NOAA's mission?
- How can we best use current and emerging environmental data?
- How can modeling be best integrated and improved with respect to skill, efficiency, and adaptability?
- How can we support informed public response to changing environmental conditions?
- How can we improve the way scientific information and its uncertainty are communicated?

In addition to these plans, NOAA convened five workshops focused on major science challenges confronting the agency. Importantly, all of these workshops included participants from the external community as well as NOAA's services and research organizations. Of the five NOAA Science Challenge Workshops, three were led by PSD scientists: Toward Understanding and Predicting Regional Climate Variations and

Of the five NOAA Science Challenge Workshops, three were led by PSD scientists.

Change, Understanding the Water Cycle, and most recently, on Predicting Arctic Weather and Climate and Related Impacts. Recommendations from these workshops have contributed to this Plan's goals and objectives.

Needs and gaps in NOAA services provide critical direction to PSD research efforts. For example, PSD is currently working closely with the NWS in the development of the Next Generation Global Prediction System. This close interaction will continue in upcoming years. PSD is also engaged with NWS and NCDC in developing the next generation of the most widely used dataset in all of the geosciences: the NCEP-NCAR reanalysis. More broadly, rapid changes in the Arctic and possible links with lower latitudes have large implications for NOAA's mission, affecting all of NOAA's services. Because of this, PSD scientists work closely with NOAA services counterparts through the NOAA Arctic Task Force and other cross-NOAA teams to define highest priority research needs. Gaps and challenges in NOAA services have also been identified in recent NAS reports, such as those on improving NOAA's intraseasonal to interannual (ISI) predictions and on characterizing and communicating uncertainty in weather and climate forecasts. These are very high priority areas for NOAA. PSD has established strengths that can contribute to essential services improvements in these areas.

SOCIETAL NEEDS

Addressing societal needs for environmental information is vital to PSD's research strategy.

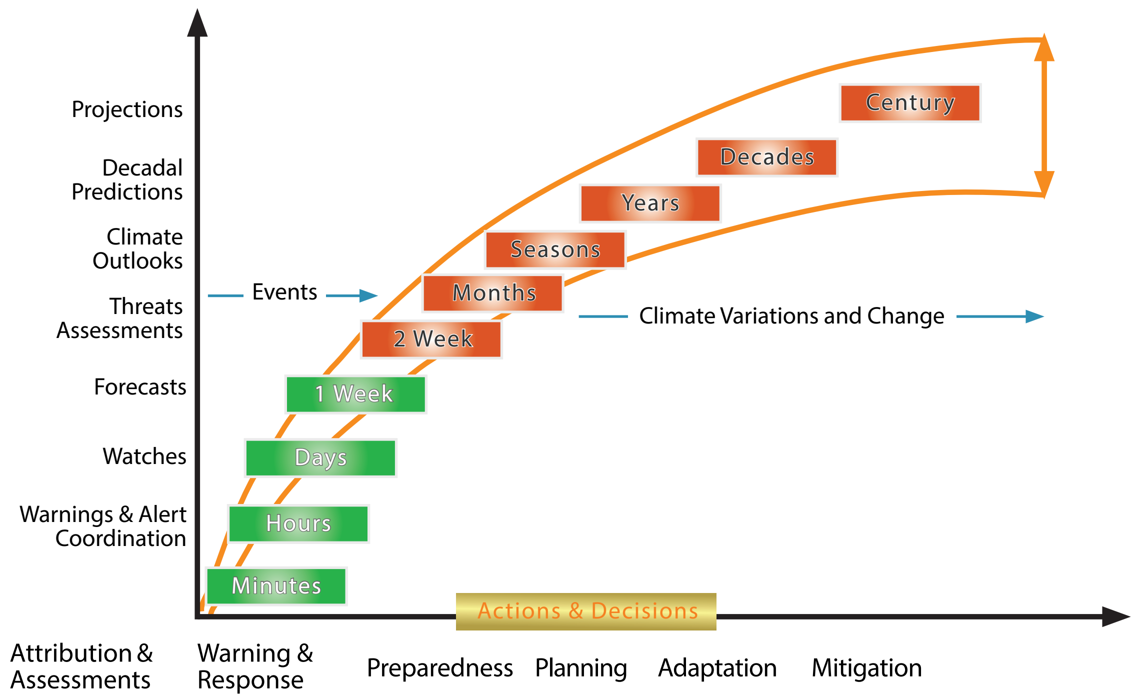
Addressing societal needs for environmental information is also vital to PSD's research strategy. As illustrated in Figure 2, the needs extend across time scales from weather to climate, and inform decisions that extend from near-term actions in preparing for and responding to weather hazards, planning to address weather and climate-related risks and opportunities over weeks to a year, and adaptation, risk management and mitigation decisions that have a time horizon of many years to decades. Across all time scales, improved science information is required to better anticipate and prepare for extreme events and to better manage the nation's water resources. These needs are becoming increasingly urgent, related in part to increased vulnerabilities of society and ecosystems to a variable and changing climate. In addition, rapid changes in the Arctic have increasingly large implications for the nation's economy, national security, and international policy. Thus, three major societal challenges that will critically affect NOAA's mission for the foreseeable future are:

- Reducing the vulnerability to extreme weather and climate.
- Preparing for drought and water resource challenges.
- Anticipating and preparing for Arctic environmental change and its impacts.

National needs in these areas serve as key societal drivers for PSD's future research directions. PSD has scientific capabilities necessary to make important contributions to NOAA and the nation to help address these challenges. Accordingly, PSD's strategy will emphasize research necessary to advance NOAA capabilities in these three critical areas.

Figure 2

NOAA environmental information to inform actions.



OTHER NATIONAL AND INTERNATIONAL DRIVERS AND EMERGING OPPORTUNITIES

NOAA's Mission Goals, current and emerging services requirements, and societal needs are primary but not exclusive considerations for developing PSD's strategy. PSD's research occurs within the context of broader national and international science activities. PSD recognizes these relationships and, as able, supports national and international research programs. Major programs whose science priorities influence PSD's strategy include the U.S. Global Change Research Program (USGCRP), World Climate Research Programme (WCRP), the World Weather Research Programme (WWRP) and U.S. interagency weather research programs, and the U.S. Arctic Research Plan and Interagency Arctic Research Policy Committee (IARPC). PSD scientists have been lead authors and contributors to the Intergovernmental Panel on Climate Change (IPCC) reports, and are likely to continue to play in such roles in the future. PSD scientists also provide significant contributions to other large national and international programs and projects, for example, as chairs, co-chairs, or members of science steering committees, on expert working groups or in other significant capacities. These service contributions will continue over the next five years.

The full scope of PSD connections to national and international science programs and research priorities will not be discussed here, although a few major trends, needs, and opportunities are important to note. Continuing national and international trends in research and services toward more unified approaches to weather and climate align

PSD has essential scientific expertise in areas central to achieving objectives for improving process understanding in the Arctic.

very well with PSD's core research strategy. Similarly, the trend toward more integrated Earth system approaches matches long-term research priorities in PSD. Pressing needs are to more rigorously link physical science to impacts for improved hazard early warnings, preparedness, and adaption. This is a gap area for both weather and climate. In addition, better characterization and communication of uncertainty in weather and climate forecasts are urgently needed, as highlighted in the recent NRC Report Completing the Forecast, and more broadly across NOAA science in a NOAA workshop on Strengthening NOAA Science. PSD has strengths that can contribute toward addressing these needs, and they are factored into PSD's strategy.

In addition to needs, there are emerging opportunities. One is the new international Polar Prediction Project (PPP) coordinated through the WWRP, aimed at improving weather and environmental prediction services for Polar Regions on time scales from hours to seasonal. Of particular interest is the PPP flagship effort, the Year of Polar Prediction (YOPP), which will coordinate intensive field experiments and process research with enhanced modeling efforts during the period 2017-2019. PPP and YOPP science objectives match extremely well with NOAA service needs for improved Arctic forecasts of weather, climate, and sea ice. PSD has essential scientific expertise in areas central to achieving objectives for improving process understanding in the Arctic. PSD also has important strengths in developing and testing observations and data assimilation systems and applying ensemble model approaches to improve predictions. PSD scientists are also providing leadership in planning a coordinated field campaign, MOSAiC, to develop understanding of ice-atmosphere-ocean processes in the rapidly changing Arctic. YOPP and MOSAiC provide exceptional opportunities to coordinate PSD research with partners across NOAA, the U.S., and internationally to achieve major improvements in NOAA models and predictions of weather, climate, and sea ice in the Arctic region, as well as clarify links between changes in the Arctic and weather and climate at lower latitudes. Finally, a significant part of PSD's strategy will be to continue to allow flexibility for both the development of and response to, major new science advances whether from inside or outside PSD, as well as to provide rapid response capabilities to address unanticipated environmental or societal needs.

From the Past to the Future

The nation faces increasingly daunting challenges related to a changing environment, which will require much from NOAA. In the future, NOAA's mission will need to provide increasingly diverse environmental intelligence rapidly, accurately, and effectively. To respond to emerging requirements, we envision that over the coming decades that society will need, and NOAA will provide, integrated environmental information systems focused on critical problems affecting the nation. These integrated systems will enable decision-makers to rapidly and efficiently access information that connects seamlessly from our past to the future – where we have been, where we are now, and where we are going. This information will provide the situational awareness required to achieve

PSD can conceive and contribute to the development of integrated environmental systems that will enable decision makers to rapidly and efficiently access critical information.

community resilience and effective stewardship of our national resources within the context of multiple environmental and societal stresses.

PSD can conceive and contribute to the development of such integrated environmental information systems through its observing, understanding, and modeling capabilities, together with its extensive experience working with stakeholders, frequently in innovative partnerships. Accordingly, over the next five years PSD will build a forward-looking component of its strategy around this concept. For example, as illustrated in Figure 3, a generalization of NIDIS would be to an integrated water information system serving water management needs across a broad range of time scales, from the past to the future. PSD has much scientific expertise that it can bring to bear on this problem, from knowledge of past climate and the causes of regional floods and droughts, innovative capabilities in observations of current conditions, to predictions of the future.

Examples of potential PSD Contributions

Past to Present: Reanalyses, Attribution for floods, droughts, regional precipitation trends. Assessments of physical events, impacts and their relationships

Future: Research to improve predictions from hours to decades

Needs for observations, process understanding and user interactions extend across all time scales

Figure 3

An integrated information system for decision support on water-related risks and impacts

Another strategy that PSD will pursue over the next five years is to coordinate research through intensive efforts working together with partners focused on specific regional problems. Such efforts provide rich opportunities to accelerate science advances while also more directly assessing user needs and the applications and realizing the value of new science-based information. For example, for water-related efforts, a focus on California water issues may be particularly fruitful. This is an area where PSD has been conducting research for several years and has developed considerable expertise on floods and droughts that extends across the continuum from weather to climate. Addressing major Arctic science challenges also provides an important focused regional research opportunity where PSD anticipates coordinated efforts with NOAA and external partners over the next five years.

Some challenges can be readily foreseen: growing exposure and vulnerabilities to extreme events; increasing stresses on national and regional water resources; and the impacts and implications of a rapidly changing Arctic. Others, however, will be difficult to anticipate - there will be surprises. Because of this, PSD will need to retain flexibility and adaptability to respond rapidly to emerging NOAA and national needs. In all cases, however, addressing the challenges will necessitate the best science to inform the public and decision-makers. PSD can play an important role in helping to achieve this end.

Strategic Goals and Objectives

The previous sections provide the foundation for PSD's science strategy through 2020. From this foundation, PSD has identified two overarching goals and three priority research goals that appear particularly ripe for significant scientific advances. All goals are listed below and then discussed in more detail on the following pages. The two overarching goals reflect broad PSD research objectives that will advance physical understanding (with science-based explanations being a key product) and predictions. The three priority research goals focus on addressing major challenges for NOAA and the nation related to extremes, water, and the Arctic. They are:

OVERARCHING SCIENCE GOALS

1. Develop new knowledge and capabilities to explain observed weather and climate extremes, variations, trends, and their impacts to inform risk management and adaptation decisions.
2. Identify new sources of predictive skill and improve predictions of weather, water, and climate through observations, understanding, and modeling of physical processes and phenomena of the coupled Earth system.

PRIORITY RESEARCH GOALS

1. Rigorously characterize and predict weather, water, and climate extremes and their uncertainties to inform decision-making.
2. Develop new process understanding, observing, and modeling capabilities to predict conditions associated with too much or too little water for early warning, preparedness, resource management, and adaptation.
3. Increase process understanding of the coupled Arctic system and Arctic lower-latitude interactions to improve NOAA weather, climate, and sea ice forecasts.

Overarching Science Goal 1

Develop new knowledge and capabilities to explain observed weather and climate extremes, variations, trends, and their impacts to inform risk management and adaptation decisions.

Policy and decision makers require accurate knowledge of the factors causing high-impact weather and climate events to make informed decisions on how society should invest in critical infrastructure in risk-prone areas while ensuring resiliency. They also require knowledge of regional and seasonal differences in climate trends and variations. Regional and seasonal trends can, and often do, differ markedly from global averages, and are often much more relevant to decision-making, for example, for determining impacts and adaptation decisions in agriculture, water supply, health, energy and other sectors. Research advances are needed to provide reliable, timely explanations of the causes of high-impact extreme weather and climate events and trends to better assess and act on weather and climate-related risks. Over the next five years, PSD will work with partners to provide diagnostic explanations for the causes of extreme meteorological events and their impacts that will inform the development of new information products, including authoritative assessments for high-impact cases. The explanations will inform preparedness decisions by clarifying which extremes are transient events caused by temporary fluctuations, and which may be more likely to persist or reoccur due to changes in oceanic, land surface and atmospheric conditions. PSD will also work with partners to more rigorously characterize the linkages between the physical events and their societal and environmental impacts. The resulting information products and services will allow decision makers managing coastal, marine, water, and other critical resources to have timely access to the best available information for understanding risks related to extremes and observed trends.

SCIENCE QUESTIONS

- What are the primary explanations for observed regional climate variations and trends?
- How do climate change and decadal variations affect seasonal climate and weather extremes?
- How do the causes of recent observed extreme events compare with those of the past?
- How can the relationships between climate variations and change, extreme weather and climate events, and their impacts be made more rigorous?

PSD RESEARCH OBJECTIVES

- Improve understanding of atmospheric and oceanic variations and extremes over the past 200 years by enhancing the observational database and utilizing it in advanced data assimilation systems.

- Intercompare the latest long-term reanalysis datasets and coupled and uncoupled model simulation datasets for detection and attribution and to aid in model error diagnoses.
- Identify and explain the causes and predictability of regional and seasonal differences in climate trends, variations and high impact weather and climate events.
- Detect and attribute significant changes in weather and climate (trends, variations, extremes), to identify precursors providing early warning and informing preparedness, and to assess societal and marine ecosystem vulnerabilities to potential tipping points.
- Develop robust methods for quantifying impacts of climate change by collaborating with external research partners to connect climate attribution science findings with impacts.

INDICATORS FOR SUCCESS

- New reanalysis datasets extending 200 years are generated, distributed, and used across NOAA and the scientific community for weather, climate, and ecological applications.
- Improved detection and attribution of climate variations and extreme events resulting from the increased sample size of the long-term reanalyses and simulation datasets, and advances in physical understanding and diagnostic methods.
- Improved identification and attribution of model errors suggesting pathways to model improvements.
- Implementation of model improvements in NOAA and other national models
- Assessments explaining causes of trends, variations and high impact extreme events are developed, provided and used to increase knowledge for informed decision-making and risk management.

Overarching Science Goal 2

Identify new sources of predictive skill and improve predictions of weather, water, and climate through observations, understanding, and modeling of physical processes and phenomena of the coupled Earth system.

As discussed in Section 2 of the PSD Strategic Plan (predictability and predictions), there is a gap between the skill of current prediction systems and the theoretical limits of skill as estimated from predictability experiments. PSD intends to determine what new observations are needed to inform our understanding of poorly represented processes, as well as reduce the initial uncertainty through their assimilation. PSD will also contribute to an improved understanding of the dynamics of these key processes and their more faithful representation in prediction systems.

KEY SCIENCE QUESTIONS

- Based on recent scientific and engineering advances, what are potential capabilities for new and improved observations to advance monitoring, process understanding, and predictions?
- What improvements in global and regional climate predictions are possible?
- What changes to data assimilation methods will facilitate a more effective use of the observations to forecast and characterize weather and climate variability?
- What key phenomena and processes are represented sub-optimally in NOAA's current-generation weather and climate prediction systems, and how can their representations be improved?

PSD RESEARCH OBJECTIVES

- Develop new observational methods based on signals of opportunity (e.g., GNSS, Sirius radio, satellite TV) for measuring land, ocean, and atmospheric properties such as soil moisture, snow cover, and atmospheric water in all forms.
- Improve and expand innovative use of observing technologies, monitoring and archives of existing measurements related to fluxes of heat, momentum, and moisture to better characterize and understand key physical processes.
- Quantitatively compare observed-state variables and flux measurements with climate and weather model output to assess process realism. Use this to guide the development, testing, and choice of parameterizations of key physical processes.
- Develop improved or new parameterizations of physical processes, especially clouds, convection, stratospheric and boundary layer processes, including representations of uncertainty and indeterminacy, to improve deterministic and probabilistic forecasts.
- Identify large-scale atmosphere–ocean–land–sea–ice conditions that improve conditional forecast skill.
- Develop process understanding of aerosol impacts on weather and climate including direct (radiative processes) and indirect (nucleation processes) effects.
- Characterize and understand connections between clouds and global- and regional-scale circulations in present and future climates to enhance predictive skill.
- Develop an end-to-end understanding of the links between changes in atmospheric composition, changes in radiative fluxes throughout the atmosphere, and the corresponding response of the Earth system.
- Develop and test new methods for numerical weather-climate prediction, including the non-hydrostatic global dynamical cores and coupled data assimilation and prediction systems.

- Improve data assimilation systems for operational prediction and reanalysis through better use of uncertainty information available from ensemble prediction systems.
- Improve ensemble prediction methods, including representations of initial condition uncertainty, model uncertainty, and uncertainty in the representation of coupled modeling.
- Transition research advances into NOAA operational and research models.

INDICATORS FOR SUCCESS

- Theoretical and experimental proof of concept provided for new observational methods based on signals of opportunity.
- NOAA implements new methods to significantly increase monitoring of the environment on national and global scales by means of remote sensing to improve decision-making and monitoring products, e.g., the US Drought Monitor.
- Parameterization errors are identified and an improvement pathway is suggested.
- Improved process representations in models results in advances in model performance.
- NOAA and other national models implement the improvements and parameterization errors are reduced.
- Probabilistic forecasts become more reliable.
- Objective metrics for weather and climate prediction forecasts improve with respect to current baselines.

Priority Research Goal 1

Rigorously characterize and predict weather, water, and climate extremes and their uncertainties to inform decision-making.

Climate and weather extremes such as heat and cold waves, heavy rain events and large-scale floods, droughts, and intense tropical and extratropical cyclones profoundly affect society and the environment, resulting in loss of life, property, and natural habitat. The direct impact of extreme weather and climate events on the U.S. economy is substantial. The U.S. has sustained 178 weather- and climate-related disasters since 1980 in which overall damages/costs reached or exceeded $1 billion, with a total normalized loss exceeding $1 trillion. Providing early warning and informing preparedness requires reliable estimates of probabilities of high-impact weather and climate extreme events. Decision-makers need improved information on how weather and climate extremes are changing now, and may change in the future, especially at the scales relevant to disaster mitigation and adaptation decisions. PSD will work together with partners to improve the observations, understanding, and modeling of weather and climate extremes needed to ensure that decision-makers have access to the best available information for understanding extreme event risks and anticipating how the risks may evolve over the continuum from weather to climate.

KEY SCIENCE QUESTIONS

- What are the sources of predictable climate variations, such as tropical sea surface temperature (SST), that drive changes in climate, water, and weather extremes around the globe?
- How can forecasts, warnings, and decision support for extreme weather events be improved?
- How can uncertainties with respect to extremes be better quantified and communicated?

PSD RESEARCH OBJECTIVES

- Generate data sets for extreme event analysis such as long-term reanalyses and reforecasts.
- Develop and apply novel observational methods together with model experiments to better understand processes that make events extreme.
- Apply ensemble modeling and post-processing methods to quantify sources of uncertainty associated with predictions of extreme events for different regions and improve reliability.
- Improve the methods for the post processing of ensemble prediction data so that resulting forecasts are unbiased, reliable, and as specific as possible.
- Develop and evaluate statistical methods to relate large-scale dynamics to local extremes across forecast timescales to provide higher-resolution probabilistic forecasts of weather and water extremes.

INDICATORS FOR SUCCESS

- Reanalysis and reforecast data sets developed and applied for research and forecast improvements of extreme events.
- Processes that contribute to extreme events are determined and needs identified for observational and model systems used for monitoring and predictions.
- Uncertainties associated with extreme-event predictions are better characterized and quantified.
- Advances in ensemble modeling and post-processing methods are transitioned to NOAA models for operational predictions of extreme events, including higher spatial-resolution probabilistic predictions and improved representation of uncertainties.

Priority Research Goal 2

Develop new process understanding, observing, and modeling capabilities to predict conditions associated with too much or too little water for early warning, preparedness, resource management, and adaptation.

Given the fundamental importance of water resources to life, the environment and economy, there is an urgent need to better understand if floods and droughts are changing and, if so, how and why. Seamless water predictions are needed across time scales from hours to decades to better anticipate risks and opportunities, prepare for, and manage this critical resource. As this Plan is being written, California and other parts of the West are in the fourth year of a drought that has caused more than $42 billion in direct economic losses, largely from the agricultural sector, with further losses inevitable. Flooding affects all parts of the country, leading to loss of life, property, and an extensive range of impacts. On average, more lives are lost to floods each year than any other natural hazard. In 2011, both the Missouri and Mississippi Rivers flooded, causing tens of thousands of people to be displaced and resulting in more than $5 billion in damages. In the state of California as well as other parts of the country, flooding related to atmospheric rivers is a key concern. The timing and intensity of heavy rainfall events can play a role in amplifying or reducing the severity and duration of drought and flood impacts.

Over the coming decades, many regions and economic sectors will experience challenges from water shortages, poor water quality, and flooding. Research is needed to improve understanding and capabilities to predict conditions leading to too much and too little water. PSD will continue to work together with partners to improve the observations, understanding, and modeling of such conditions as required for early warning, preparedness, resource management, and adaption to enable the nation to address its many water-related challenges within a variable and changing climate.

KEY SCIENCE QUESTIONS

- How can we improve understanding of water in all forms to better anticipate and prepare for floods and droughts?
- How can we improve forecasts for freshwater resource management?

PSD RESEARCH OBJECTIVES

- Improve and expand measurements related to hydrometeorology using innovative ground-based in situ and remote sensing technologies.
- Employ observations to improve understanding of precipitation processes in complex terrain, assimilate land surface observations, and develop new techniques for statistical post processing to improve QPF of extreme events and their impacts on hydrologic forecasts.

- Increase process understanding of aerosol-cloud-precipitation interactions to improve precipitation predictions.
- Improve understanding of the role of tropical-extratropical dynamics and moisture transport on extreme precipitation in the Western U.S.
- Improve understanding of drought from within an evapotranspiration and evaporative demand-based context to better characterize drought early warning, onset, and severity.
- Advance understanding of regional hydrometeorological processes and land-surface feedbacks in order to develop experimental applications to support to water resource risk management in a variable and changing climate.
- Contribute to the development and application of coupled hydrologic and atmospheric modeling systems for understanding and predicting floods and communicating flood risks.
- Characterize how QPF uncertainty translates into hydrologic uncertainty through improved pre- and post-processing techniques.

INDICATORS FOR SUCCESS

- Actionable intelligence is provided to inform water management and/or ecosystem services decision-making on flood risk and water storage over time scales ranging from minutes to seasonal.
- QPE, QPF, and/or atmospheric and hydrologic model errors are identified and improvement pathways are suggested.
- QPF skill is extended to longer lead times.
- Uncertainty in atmospheric forcing and hydrologic response for extreme events is characterized and quantified.
- Results of research advances are transitioned to operational products for improved flood and drought forecasts.

Priority Research Goal 3

Increase process understanding of the coupled Arctic system and Arctic-lower latitude interactions to improve NOAA weather, climate, and sea ice forecasts.

Changes in the Arctic have been among the most striking in the world, with profound consequences for inhabitants and ecosystems in the region. Changes within the Arctic do not occur in isolation but rather can affect, and be affected by, lower-latitude processes and phenomena. Physical sciences research is needed that integrates observation-based process understanding and modeling to advance NOAA's abilities to provide early warning of hazards related to Arctic weather, climate, and sea ice. Research is also needed to better understand causal links between Arctic warming, loss of sea ice and midlatitude weather and climate. Improved observations and better understanding of the physical processes of the coupled ocean-ice-atmosphere system are also required to advance our ability to anticipate longer-term changes in the Arctic climate system. The challenge of improving forecast skill of Arctic sea ice across weather and climate timescales has become increasingly urgent for NOAA's services, and is required to respond to rapidly emerging national needs related to the ongoing profound changes in this region. Over the next five years, PSD will work together with partners to address present and anticipated new requirements for predictions of Arctic weather and climate and related impacts, including sea ice, and improve understanding of the linkages between weather and climate in the Arctic and lower latitudes and their implications for NOAA's forecasts and services.

KEY SCIENCE QUESTIONS

- What are the processes that control the formation, longevity, microphysical and macrophysical properties of Arctic clouds, including the effects of and sensitivities to aerosols?
- How do atmosphere-surface exchanges of heat, energy, and gases drive changes in the Arctic cryosphere (permafrost, snow cover, and sea ice) and ecosystems?
- What are the two-way linkages between the Arctic and global weather and climate?

PSD RESEARCH OBJECTIVES

- Improve understanding and model representation of air-sea-ice coupling physics in the Arctic and how coupled processes affect sea-ice energy and momentum budgets.
- Observe, analyze, and contribute to model improvements of the fully coupled Arctic atmospheric system, including clouds, aerosols, radiation, composition, surface energy budgets and mesoscale circulations.
- Improve understanding and parameterizations of Arctic cloud processes including their interactions with radiation, precipitation, aerosols, boundary layer structure, and large-scale meteorology.
- Improve understanding of physical processes that connect the Arctic and lower latitude weather and climate through research to identify new sources of Arctic predictability and potential impacts on midlatitude weather and climate.

INDICATORS FOR SUCCESS

- Data collected in the Arctic region leads to improved understanding of processes, and is provided to and applied for research and applications by the broader community.
- Cloud and surface-exchange parameterizations are improved and incorporated into models.

- Statistical sea-ice forecasting models are developed and incorporated into forecast guidance.
- Model parameterizations and satellite retrievals are improved through PSD research and the use of surface-based observations of the Arctic atmosphere.
- Research results from PPP/YOPP and MOSAiC obtained by PSD scientists and collaborators contribute to quantifiable NWS forecast improvements for Arctic weather, climate, and sea ice.