WORKSHOP REPORT

Nonstationary Weather Patterns and Extreme Events

Informing Design and Planning for Long-Lived Infrastructure

ESTCP Project RC-201591

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The document was prepared by the authors as a general record of the main points and highlights of discussions during a workshop. It is not a complete record of all details discussed, nor does it interpret matters that were incomplete or unclear. All participants had the opportunity to comment on a draft of the report, and additional expert reviewer comments were sought to ensure consistency with the general state of knowledge on this topic. Statements represent the individual views of the workshop participants and do not reflect the views of their institutions or any U.S. Federal agency.

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ACRONYMS AND ABBREVIATIONS

14 WS	14th Weather Squadron (U.S. Air Force)
AIA	American Institute of Architects
ASCE	American Society of Civil Engineers
CMAP	Climate Monitoring, Analysis, and Prediction
CMIP	Coupled Model Intercomparison Project
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
ESTCP	Environmental Security Technology Certification Program
FEMA	Federal Emergency Management Agency
IPCC	Intergovernmental Panel on Climate Change
JGCRI	Joint Global Change Research Institute
LOCA	Localized Constructed Analogs
METOC	Meteorological and Oceanographic
MILCON	Military Construction
NCA	U.S. National Climate Assessment
NOAA	National Oceanic and Atmospheric Administration
PNNL	Pacific Northwest National Laboratory
RCP	Representative Concentration Pathway
SERDP	Strategic Environmental Research and Development Program
SON	Statement of Need
UFC	Unified Facilities Criteria
U.S.	United States
USGCRP	U.S. Global Change Research Program

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ABSTRACT

This is a report of a workshop sponsored by the Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP). The workshop explored information needs and sources for planning resilient infrastructure and installations when historical climate records indicate statistical patterns of extreme or average conditions are changing (i.e., when they are "nonstationary") and no longer provide a reliable guide to planning for the future. The workshop brought together practitioners from planning, engineering, and architectural communities; members of the science community conducting research on Earth systems, environmental change, and risk assessment and communication; and operations and real property managers. Practitioners at the workshop highlighted the need for information that (1) focuses on a wide range of hazards and thresholds; (2) provides most likely conditions and maximum credible extremes for a number of periods and mean recurrence intervals; (3) analyzes historical and projected conditions at high temporal and spatial resolution for specific sites; and (4) considers information requirements by discipline and location. The workshop identified ideas for SERDP/ESTCP initiatives to support the U.S. Department of Defense (DoD) and advance research and practice more generally. The ideas span the spectrum from applications to basic research and have the potential to accelerate near-term availability of information for practitioners as well as to improve basic knowledge of relevant environmental change processes.

EXECUTIVE SUMMARY: KEY MESSAGES

The U.S. Department of Defense (DoD) relies on a large number of installations with extensive supporting infrastructure to prepare for and execute missions to defend U.S. national security interests. Many installations and their supporting infrastructure systems (e.g., energy, transportation, water resources, medical services) are located in areas prone to natural hazards such as floods, coastal storm surge, droughts, extreme temperatures, fires, winds, and other events.

Engineers, architects, and planners are responsible for designing facilities that are suited to expected conditions and that provide acceptably low failure risks over the facilities' service lives. Complying with standard code requires design professionals to rely on design assumptions that include a wide range of climatic attributes regarding the frequency, magnitude, intensity, and seasonality of climate. For infrastructure projects, relevant design life often exceeds 30 years—a period of time of sufficient duration that climatological shifts may have relevance. These shifts in the statistical properties of climate and environmental conditions are referred to as *nonstationarity*. Nonstationarity is important to DoD because the risk inherent in design may become incorporated into the form and function of the infrastructure. Designs built upon faulty assumptions, or assumptions with non-quantified risk, pose hidden risks to DoD mission capabilities, readiness, safety, and budget.

While there is high confidence within the scientific community about long-term trends at broad scale, there is uncertainty about future statistical properties of climate at time and spatial scales required for planning and design purposes. Information routinely produced by the research community does not address the information needs of design practitioners at the decadal and local spatial scale, and in an actionable form. Assessments, for example, typically focus on changes in average conditions across large regions and do not include more tailored information about extreme events. There is a gap between climate science and planning/design practice that needs to be bridged.

To explore potential research and development needs and opportunities for improving information for management of nonstationarity as it affects DoD planning, the Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) convened a workshop that brought together (1) practitioners from planning, engineering, and architectural communities; (2) members of the science community; and (3) operations and real property managers. This report describes several of the topics addressed and highlights some of the main "takeaways" noted by participants during discussion.

Practitioners were asked to reflect on the current state of practice in their various areas of professional responsibility. Their comments touched on four issues: (1) mandates and management context for consideration of nonstationarity; (2) approaches to incorporate uncertainty in planning and design processes; (3) information flows, both from climate science to design practitioners, and from practitioners to decision makers; and (4) desired characteristics of information sources.

The DoD routinely makes land-use and installation decisions at a local level, usually on a project-by-project basis. Decisions made across many projects sum to multi-billion dollar budgets and have consequences for the overall DoD mission. There are important exceptions when decisions about long-term infrastructure needs are made at an enterprise level, such as the Base Realignment and Closure (BRAC) process. Given this project-specific decision environment, the challenge is then for DoD planning and design professionals to be armed with tools and information to understand, plan for, and implement robust and adaptable designs that meet the needs of decision makers entrusted with the DoD mission today and in the future. These tools must have no hidden assumptions and provide understandable results communicated in standard, regularly-used metrics.

To assess whether non-stationarity is an important issue and, when it is, to develop adaptable designs, the practitioners highlighted the need for information that:

- Focuses on *specific hazards and thresholds*;
- Provides both *most likely conditions* and *maximum credible extremes* for a number of periods and mean recurrence intervals for 20, 50, and 100 years in the future;
- Analyzes historical and projected conditions at *high temporal and spatial resolution* for specific sites; and
- Considers requirements by *design discipline* (architecture, spatial planning, structural engineering, mechanical engineering, etc.), *system* (transportation, water resources, etc.), and *location*.

The planning and design professionals who participated in the workshop stressed that for information to be useful, it needs to be presented through application-oriented fact sheets, data sets, maps, scenarios, and other tools. This information needs to be developed using approved methods and sourced through authoritative, officially-designated sources such as data portals. During the discussions, participants suggested that DoD meteorological services/agencies might be augmented to interpret and provide needed climate information, and that installations themselves may be able to play a role in collecting and tracking installation-specific information on hazards, thresholds, and post-event impacts and consequences. Practitioners urged that rather than waiting for "perfect" tools and information, risks to DoD can be more effectively managed if "good enough" information is released sooner, and accompanied by analysis of uncertainties and effective communication of levels of confidence. Technical guidelines and training for practitioners on the uses and limits of available information is also needed.

Scientists researching various aspects of physical climate, hydrology, coastal dynamics/ processes, and environmental risk assessment were asked to reflect during the workshop on the current state of science relevant to understanding nonstationarity and its implications. Their comments addressed a number of topics, including: (1) evidence to support the conclusion that "stationarity is dead;" (2) potentially viable methods for assessing nonstationarity; and (3) ongoing projects and research opportunities.

Presentations and discussion at the workshop built on current research in physical climate, hydrology, coastal dynamics/processes, ecology, and environmental risk assessment and communication. Participants noted the importance of the United States maintaining leadership in global change research and the need to support activities such as the U.S. Global Change Research Program.

They also noted these programs need to be more responsive to the needs of practitioners. Specific methods discussed included quantifying changes in indicators of extreme events, producing histograms of those indicators, and applying extreme value analysis. These and other similar methods were seen as providing climatic design parameters, although a number of scientific challenges and uncertainties were identified. "Downscaling" (using coarse-resolution model output to interpolate finer-scale information) was identified as another essential method for providing information for specific sites. Multiple downscaling approaches are available, and more evaluation and guidance is needed about which methods produce information that is accurate and appropriate (cautions were raised about the use of seemingly precise but inaccurate information). It was noted that data and information accessed from research community portals had the potential to be useful, but that it was often not analyzed or presented in ways that were relevant to applications or comprehensible to practitioners.

A key insight from the workshop is that sustained interaction of design professionals and the research community is needed to improve information for risk management. This is a grand challenge on many levels including identifying the problems that need to be addressed, breaking down barriers to communication including developing shared vocabulary, exchanging information about different methods and the assumptions embedded in them, and designing shared approaches that are both scientifically robust and decision relevant.

Synthesizing across practitioner and research community perspectives, the workshop identified a number of ideas for use-inspired research that would address the needs of DoD and civilian design communities. The list that follows does not include all the ideas proposed at the workshop but rather represents the author team's sense of greatest need and opportunity (in no particular order):

- Risk framing: encourage development, evaluation, and adoption of risk-based approaches to plan and design for nonstationarity. Such approaches start from prioritizing what is at risk and include evaluation of the likelihood and consequences of "tail risks" (hazards and conditions that may be unlikely but would have very detrimental impacts).
- Extreme events: improve understanding of extreme events, including probabilistic analysis and fusion of traditional and nontraditional indicators.
- Downscaling: validate current methods, develop and test new approaches, and provide guidance for different situations, locations, and variables.
- Intensity-Duration-Frequency (IDF) of storms: address a widely-stated need by focusing on improving projections of storm direction, intensity, and duration.
- Coastal risk dynamics: conduct research to improve projections of interactions of sea-level change, storm surge, precipitation, and land-based flooding at scales relevant for specific DoD sites.
- Modeling and scenarios: improve modeling and tools to develop, apply, and evaluate scenarios of multiple interacting stresses, including training in underlying assumptions and application of scenarios.
- Economic and decision-relevant metrics: develop methods that estimate and communicate impacts using cost or other mission-relevant performance metrics familiar to decision makers.

- Sensitivity and adaptive capacity: identify approaches for analysis of spatial distribution of vulnerabilities to differentiate systems and sites that face higher inherent risks.
- Technology transfer tools: develop tools and a "lexicon" to improve communication among scientists, engineers, architects, planners, and other users.
- Materials engineering: conduct research on materials fragility and implications for infrastructure/building design.
- Visualization of uncertainty: improve approaches for identifying and characterizing confidence and uncertainty (including developing shared terminology and understanding of different types of uncertainty conceptualized across practitioner and research communities) and for providing better graphical representations of uncertainty that are useful in decision-making processes.

Several opportunities seem particularly relevant for the SERDP/ESTCP program to improve resources for DoD design professionals. One cross-cutting suggestion was to engage civilian professional associations and groups in SERDP/ESTCP activities. Examples of these groups include the American Society of Civil Engineers and American Institute of Architects, both of which are currently developing methods and standards appropriate for nonstationarity. Additional suggestions for increasing attention to these issues in SERDP/ESTCP include:

- *Infrastructure innovation communities of practice*: SERDP/ESTCP could establish "communities of practice" focused on specific DoD design challenges. These groups would enable practitioners in specific areas of practice to meet for a sustained period with researchers to identify information needs, tap available information, conduct training, and spin off ideas for new research to innovate resilient infrastructure and installations.
- *"End-to-end" research in SERDP Statements of Need*: SERDP could encourage "co-production" of use-inspired fundamental research by inviting and giving favorable consideration in its Statements of Need to proposals that include (1) fundamental science, (2) application, and (3) evaluation of utility by project teams that include both practitioners and researchers.
- *Near-term information delivery improvement*: SERDP/ESTCP could survey information needs of DoD practitioners and focus its Statements of Need of these topics, e.g., accelerating analysis of observational and model archives and other information on priority extreme events. Several examples of such projects discussed at the workshop are elaborated in Appendix C of this report.

1.0 BACKGROUND

The U.S. Department of Defense (DoD) relies on a large number of installations with extensive supporting infrastructure to prepare for and execute missions in support of U.S. national security interests. The DoD is responsible for some 7,000 sites (of which approximately 510 are active installations), 24.9 million acres of land, and numerous activities and services (DoD 2015). Many installations and their supporting infrastructure systems (e.g., energy, transportation, water resources, medical services) are located in areas prone to natural hazards.

Engineers, architects, and planners are responsible for designing facilities that are suitable to expected conditions and that provide acceptably low risks of failure over the service life of the facilities. Relevant exposures include the effects of extreme weather and climate such as floods, coastal storm surges, droughts, extreme temperatures, fires, winds, and other hazards.

Evidence is strong that properties such as mean, variance, skewness, and kurtosis of many climate-related hazards are no longer constant over time (i.e., are *nonstationary*), leading to a wide range of impacts (IPCC 2013, Melillo et al. 2014, Cheng and AghaKouchak 2014). Detection and attribution of changes in environmental conditions resulting from the interactions of natural and human causes is a scientifically complex challenge. However, much progress has been made: the null hypothesis that no change has occurred has been tested and invalidated in many systems and geographies at scales from local to global; and observed changes in specific locations have been attributed to unique combinations of natural and human factors. Major contributors to these changes and impacts include socio-economic factors such as alteration of land use and cover (Tollan, A. 2002, Chang et al. 2017), infrastructure that is over-taxed and/or in poor condition (ASCE 2017a), and changes in climate resulting from interactions of natural variability and human-induced change (IPCC 2013, e.g., Dankers et al. 2014). Projections that account for all these factors developed using coupled Earth system, hydrologic, infrastructure, and ecosystem models portend even larger changes in the future (IPCC 2013, Melillo et al. 2014, Hall et al. 2015). While contributions to changes and impacts are broad and encompass multiple factors, the DoD's Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) workshop that served as the foundation for this report primarily focused on the climate aspect of the nonstationarity problem.

All design assumptions inherently possess risk, but the assumption of stationarity in a nonstationary environment introduces the potential for hidden risk that is sufficient to undermine design. Facilities and other infrastructure with multi-decadal-expected service lives may become vulnerable and unfit for their purpose, with commensurate risk to the mission, readiness, safety, and economy. As a result, either nonstationarity should be taken into account when planning and designing new infrastructure and during modernization of existing assets, or the risk of not accounting for nonstationarity should be quantified. Failure to do either can result in increased maintenance costs, failure rates, closures, and even morbidity and mortality with negative impacts to mission capabilities and attainment. Different approaches than simply using historical climate to determine the environmental operating envelope or design criteria for infrastructure or operational planning are needed.

While there is high confidence within the scientific community in long-term trends at broad scale, there is scientific uncertainty about future statistical properties of climate at time and spatial scales required for planning and design, and for assessing future operational risks. Information routinely produced by the research community does not address the information needs of design practitioners.

Assessments, for example, typically focus on changes in average conditions across large regions and do not include more tailored information about extreme events. The American Society of Civil Engineers (ASCE) and others point to a "gap between climate science and engineering practice" that needs to be bridged (ASCE 2015).

To explore potential research and development needs and opportunities for improving collaboration between researchers and practitioners, the SERDP and ESTCP convened a workshop, with support from Pacific Northwest National Laboratory's (PNNL's) Joint Global Change Research Institute (JGCRI).[1] The workshop brought together (1) planners, engineers, and architects from DoD, several DoD services, and other Federal agencies with responsibility for DoD's fixed infrastructure and installations (referred to as "practitioners" in this report); (2) researchers working on climate change, hydrology, sea-level and coastal processes, and risk assessment/communication (referred to as the "science community"); and (3) managers from DoD and other agencies responsible for overseeing various aspects of operations and real property investment and management ("decision makers"). Participants discussed (1) ongoing research on nonstationarity in climate and related environmental phenomena; (2) planning, engineering, and architectural design processes that use or require analysis of climate hazards; (3) the use and adequacy of currently available information, including opportunities for improving applications; and (4) research needs. Through the workshop, SERDP and ESTCP sought to support DoD's installation and infrastructure needs by identifying ideas for future Statements of Need (SONs) for research and applications.

This report describes several of the topics addressed and highlights some of the main "takeaways" noted by participants during discussion. The workshop format emphasized discussion and included only a few introductory presentations. In presenting these insights, we do not follow the chronological sequence of the agenda, but rather group related comments by theme. The workshop followed the Chatham House Rule,[2] so comments are not attributed to specific participants.

[1] SERDP supports research, development, and evaluation of tools to assess and manage environmental factors that affect DoD missions. The "adaptation" thrust area within SERDP's program on Resource Conservation and Resilience supports research to provide insights about future conditions, establish the implications for DoD missions, identify feasible and cost-effective adaptations, and better inform decision makers. ESTCP supports "technology transfer," in this case transitioning mature scientific results from SERDP studies to application. PNNL and JGCRI are part of the Department of Energy (DOE) laboratory system (DOE participates in SERDP) and conduct research, modeling, and integrated analyses at the interface of human, energy, and environmental systems.

[2] https://www.chathamhouse.org/about/chatham-house-rule.

2.0 PRACTITIONER PERSPECTIVES ON RISKS AND MANAGEMENT OF NONSTATIONARITY

Practitioners (planners, engineers, and architects, as defined above) were asked to reflect on the current state of practice in their various professional areas of responsibility. This section aggregates comments throughout the workshop on four topics of particular interest to the practitioner community: (1) mandates and management context for consideration of nonstationarity; (2) approaches to incorporate uncertainty in planning and design processes; (3) information flows, both from climate science to design practitioners, and from practitioners to decision makers; and (4) desired characteristics of information sources.

2.1 MANDATES AND MANAGEMENT CONTEXT FOR CONSIDERING NONSTATIONARITY IN PLANNING AND DESIGN

Practitioners—whether in civilian or Federal service—called attention to their responsibility to consider the implications of nonstationary climate and environmental conditions in planning, programming, and designing facilities. For DoD, the implications extend to maintaining a large and diverse set of installations and infrastructure, managing ecosystems used for training and testing purposes, and safely conducting activities to train, deploy, and sustain U.S. warfighters and support personnel. In a number of fields, professional codes of ethics and practice have been updated to require consideration of anthropogenic climate change so that facilities can withstand the evolving environmental conditions that will occur over their design lifetimes.

Practitioners at the workshop noted the importance of the authority under which they consider the effects of climate change and other global environmental changes in planning, engineering, architecture, management, or budget programming decisions. Multiple research studies demonstrate changes are occurring and can lead to significant impacts. Technical guidelines from civilian professional groups such as ASCE and American Institute of Architects (AIA) are being developed to guide practice, and these are often adopted by the government. For example the Office of Management and Budget (OMB) Circular A-119 (OMB 2016) directs agencies to use voluntary consensus standards in lieu of government-unique standards, except where inconsistent with law or otherwise impractical. Moreover, some directives require DoD and Service personnel to consider nonstationarity, e.g., recent Quadrennial Defense Reviews and DoD Directive 4715.21 ("Climate Change Adaptation and Resilience"), which is currently under review. Such mandates establish general requirements but do not include specific design guidance/policy on how to incorporate nonstationarity. As one participant noted, "if we don't have an instruction or specific policy, we probably won't do it or won't have the funding to do it." Specific authorities to implement this work are being rescinded and/or consideration of nonstationarity is not prioritized, which hampers prudent Federal investment and avoidance of unnecessary future costs.

Several participants expressed the view that they needed to work within existing long-standing management processes. For example, consideration of nonstationarity could be incorporated into existing areas of Facilities Investment and Management within the Office of the Assistant Secretary of Defense for Energy, Installations, and Environment.[3] These areas include: installation master planning, facility planning, the military construction (MILCON) program, facility sustainment, recapitalization and facility restoration, and demolition and disposal of excess facilities.

[3] http://www.acq.osd.mil/eie/FIM/FIM_Program_Areas.html.

Another ongoing process that can incorporate consideration of nonstationarity described at the workshop is the Unified Facilities Criteria (UFC) program, which governs the facilities and infrastructure component of the Defense Standardization Program. The UFCs provide criteria that apply to many aspects of architecture and engineering pursued by military departments and defense agencies. As one participant noted, "you need to follow them or ask for a waiver." Participants pointed out that there is not much in the UFCs related to climate change—they are based on specifically-defined periods of historical climate observations. If improved information on future conditions could be provided in ways that enabled the information to be integrated into such ongoing processes, it would be possible to compare the costs and benefits of different design options in the same context already used to analyze planning and design needs and options.

Several practitioners discussed the nature of the DoD's day-to-day work on installations and various types of infrastructure. They noted that the DoD does not typically make multi-billion dollar investments in single decisions. Instead, for much of its infrastructure work, it is a "small project agency," and many decisions are made on a project-by-project basis. At the same time however, participants noted that many such decisions are made, summing to large budgets and potential implications for DoD missions. There are important exceptions, however, such as the Base Realignment and Closure (BRAC) process, where decisions about long-term infrastructure needs are made at an enterprise level. The individuals making these decisions do not have time to do in-depth work on nonstationarity per se. They need information now on how to deal with the new types of uncertainty that nonstationarity brings into their work. In the absence of this information, they assume stationarity, and every year that nonstationarity information is not forthcoming, decisions made in the infrastructure community lock in more and more risk, which is what drives the interest of a lot of infrastructure development practitioners.

Working within existing processes in this kind of small-project environment requires information that meets several characteristics. First, information needs related to specific hazards and their thresholds must be identified. Second, authoritative site-specific data analyzing historical and projected probabilities of conditions (particularly extreme events) must be developed, which requires downscaling and other approaches. Third, the consequences of nonstationarity and the potential benefits of robust and adaptable designs (which often have higher initial cost) *must be provided to decision makers in terms that they understand and that are comparable to regularly used metrics*. If decision makers do not see estimates that incorporate these factors, then they assume there is no impact; they erroneously interpret the lack of information as "no impact." Each of these characteristics was touched on in a number of short comments and workshop discussions focused on the current state of practice in the practitioner community.

2.2 UNCERTAINTY IN PLANNING AND DESIGN PROCESSES

Incorporating uncertainty in decision making is not a novel challenge. In intelligence, military strategy, medicine, drug testing/approval, environmental regulation, economic policy, and many other areas, practitioners have grappled with how to assess, communicate, and apply uncertain information. Engineering, architecture, and planning have been among the more successful fields in developing a variety of rigorous methods for accounting for uncertainty in their work (e.g., Ayyub 2014).

Typically, statistical methods are employed to develop ranges of estimates of future conditions and safety, or performance margins are used to ensure that infrastructure is able to operate within expected ranges. There are multiple sources of uncertainty that need to be considered in any design process, including factors that could change demands for services such as socio-economic factors (e.g., migration, the pace and character of economic growth, and changes in preferences), changes in performance of key technologies, alterations in environmental factors such as land cover and the composition of ecosystems, and of course climate-related hazards and conditions. Engineers typically classify uncertainties into two types: natural randomness (aleatory uncertainty) and uncertainty due to limits in knowledge (epistemic uncertainty) (Ayyub 2014). If climate conditions were stationary, uncertainty analysis could be based solely on observations. An acute challenge in assessing uncertainty related to climate nonstationarity is that because models play such a central role in projecting future conditions, the logic of climate models is difficult to convey, and thus users may be prone to either discount the information (Moss 2011, Pidgeon and Fischoff 2011) or be overconfident in model results without appreciating the inherent uncertainties involved.

In discussions at the workshop, participants described several methods for accounting for uncertainty in planning and design. One approach, termed the "*observational method,*" employs adaptive design principles that plan structures in a way that they can be augmented during their service life as conditions evolve and information about potential (unfavorable) conditions improves (ASCE 2015). For another method, rather than using a "predict-then-act" framework that starts with pre-defined views of the future and identifies risks of what can go wrong, it starts with the decision that needs to be made and determines the ways in which the future would have to unfold to change the decision made (e.g., Brown et al. 2012, Lempert 2013). These *robust decision-making* methods are particularly appropriate when uncertainties are deep, and thus probabilities are not well characterized.

There was also discussion of approaching the issue of nonstationarity in planning and design more like a risk assessment issue, adapting practice in toxicology, nuclear safety, reinsurance, or financial markets, among others. This would depart from the dominant predict-then-act conceptual framework, which requires predictions of what will happen in the future, specifically probabilistic information on occurrence of different hazards. An approach that starts from the concept of "risk tolerance" would incorporate a number of core principles or steps, including: (1) define what we value (what is at risk) and (2) what we wish to avoid (consequences), (3) conduct analyses to identify what risky outcomes are possible and how likely they are to occur (probability), and (4) consider worst plausible cases as well as what is "most likely" to happen.

A risk-based approach would lead to a focus on high-value assets—those expected to have multi-decadal service lives and for which there is a limited ability to adapt, change, or revisit a decision. Participants highlighted the need to screen mission-essential installations and systems that have long expected lifetimes and that are potentially affected by nonstationary conditions to identify those that may be at risk. In addition, plans for renovating/reconditioning existing or new long-lived systems should be developed to account for additional uncertainty resulting from increased uncertainty in exposures to extreme (or average) conditions, including intensity, frequency, duration, timing, and other aspects. Finally, a risk-based approach requires methods for evaluating consequences and their likelihood (from impacts modeling to stakeholder elicitation) and more careful attention to understand the likelihood of "tail risks" (hazards and conditions that may be unlikely but would have very detrimental impacts) (e.g., Ayyub 2014).

Several participants suggested that the need for risk-based approaches itself defines the need for research on decision making and decision analysis methods applied to DoD planning/design contexts.

2.3 INFORMATION NEEDS

Throughout the workshop, practitioners highlighted a range of information needed for planning, architectural, and engineering analysis. These information needs vary by *profession and discipline* (architects' needs are distinct from those of engineers, and different disciplines of engineers will have different needs), *system* (transportation, water resources, communications, etc.), and *location* (given differences in hazards likely to be experienced). A number of organizations regularly compile loads and design standards for specific types of infrastructure and hazards (e.g., ASCE 2017b), and these highlight thresholds or events that should be used as design events (e.g., "the flood having a 1% chance of being equaled or exceeded in any given year"), but often do not direct practitioners to sources of this information. In cases where needed data are provided, stationarity is assumed. The workshop was not structured to recompile these information needs, although it was suggested by some members of the research community that it would be a useful exercise for DoD practitioners to identify their priority needs for this information. Here, we briefly highlight several cross-cutting issues regarding needed information that were mentioned in discussion.

Probabilistic information. Many practitioners highlighted the need for probabilistic information on hazards. However, this need serves to illuminate an important knowledge gap that is often neglected in the practitioner community. Notably, in discussions of hazards, there are two different types of probabilities. Bayesian probabilities speak to the degree of belief in a particular outcome, e.g., the "most likely" events or the probability of a "worst case" or "maximum credible" event for which infrastructure should be designed. Frequentist probabilities deal with return periods (e.g., 100-year floods) and are derived from observations of past events. Workshop participants noted the importance of highlighting these differences for decision makers to avoid misinterpretation of information.

Practitioners at the workshop identified a need for both types of probabilistic information. In civil engineering, for example, information on Bayesian probabilities is needed to understand implications of design choice for serviceability, health/safety, and property protection. In architecture, Bayesian probabilities are important for designing many aspects of building enclosure assemblies, both above and below grade, including selecting materials that will be sufficiently durable, given expected lifetime. On the frequentist side, a wide range of return periods is needed based on assessment of acceptable risk (e.g., a 100-year event representing a 0.01 probability of exceedance). It was pointed out in one example that characterizing hazards in return periods, which is the inverse of annual probabilities, is important because it facilitates analysis of the validity of load/resilience factors calibrated to achieve acceptable risks. High temporal resolution (often hourly) and spatial resolution (as fine as meters for hazards such as storm surge) are needed for designing structures and systems for particular locations. More specifically, participants argued that the planning, design, and engineering communities need:

- Authoritative projections of the design basis (most likely) for climate/weather extremes 20, 50, and 100 years in the future for Mean Recurrence Intervals of 10 to 1000+ years (annual probabilities of being exceeded of 0.1 to 0.001)
- Authoritative projections of the maximum credible (worst case) climate/weather extremes 20, 50 and 100 years in the future for Mean Recurrence Intervals of 10 to 1000+ years (annual probabilities of being exceeded of 0.1 to 0.001)

- Improved information and methods for estimating implications of changes for costs and mission attainment, including potential benefits of adaptation measures that require additional costs and/or deviate from established standards or requirements

Identify information requirements. Beyond listing specific climate parameters and types of analysis needed for determining design specifications, practitioners also discussed the need to identify information requirements by backing them out of economic and other metrics used in making siting, design, and other decisions. Nonstationary conditions will alter expected cost, performance, and compliance profiles of built and managed natural infrastructure over time. Several prior SERDP projects were mentioned that included extensive interactions with installation managers and planners that identified ongoing changes in cost and performance of both built infrastructure and "soft" assets, e.g., ecosystems, health, and readiness (e.g., Garfin et al. 2017, Moss et al. 2016). The question becomes, how will a changing environment affect these costs and benefits? This issue highlights the need for approaches and data to support monetization/valuation, including better data on adaptation costs and benefits.

Others. Several participants noted it would be useful to work backwards from cost or performance-related metrics to identify the climate and other environmental information needed to assess potential damages, costs of adaptation measures, and effects on performance. This would increase attention to "vulnerability"—that is to the spatial distribution of sensitivity and adaptive capacity in addition to probabilistic climate information about exposures. Other participants noted that costs need to be conceived of broadly—it is usually *mission considerations* that drive spending, not the other way around. Several others pointed out the importance of thinking not just about individual assets and installations, but about portfolios of assets, considering how they work as a system, and how additive effects of failures across a portfolio could lead to high rebuilding/recovery costs and eventual insolvency. Structuring the problem this way starts from the information needed to inform practitioners, and then uses this information to prioritize variables for more detailed analysis, including analysis of probability distributions.

Relevant time scales. There was a debate among practitioners regarding what time scales of climate information were relevant. This issue was not resolved at the workshop, and continues to be a source of confusion in discussions between practitioners (who define time frames in terms of their design challenges), the meteorological community, and climate scientists. Some argued that nonstationarity needed to be considered in terms of mission requirements—18–24 months to several decades for long-range planning. It was noted that the Meteorological and Oceanographic (METOC) community of interest publishes a handbook that includes thresholds for different operations and platforms (Section 12: METOC Impacts on Operations, U.S. Joint Forces Command 2011). This can be useful for identifying potential changes in incidence over time of events that would directly affect different types of combat operations. Others argued that blurring the distinction between weather and climate and focusing on short-time horizons would confuse the issue. This group felt that it was better to focus on decadal and longer periods, and not to frame the issue as "climate change," but rather to analyze whether/how infrastructure and activities would be affected as they are exposed to specific hazards. Importantly, many of the largest issues with stationarity do not emerge until a few decades out.

Uncertainty quantification and trustworthiness of the data and models. An important consideration that emerged throughout the workshop was uncertainty quantification and trustworthiness of the data and models. Workshop attendees from all disciplines identified the importance of assessing and communicating the reliability of the data, as well as the validity of the models and the assumptions under which they are suited to operate.

2.4 CHARACTERISTICS OF INFORMATION SOURCES

Discussion at the workshop focused on the need for definitive sources of information; the potential use of DoD and Service capabilities, including on military bases; as well as the potential sources of information in products developed by the research community.

Definitive sources of information. A widely-held view of practitioners at the workshop was that information needed to come from authoritative, officially-designated sources using approved methods. For DoD purposes, the data need to be provided and backed by the Federal Government and delivered through official data portals. Participants pointed to data and information resources available from the U.S. Army Corps of Engineers and also the U.S. Department of Transportation. Policies and procedures need to be established for updating information based on changing needs and science; information needs to be documented and timestamped when it is updated, and old data sets need to be archived so that practitioners using the data can document what was available when a design was developed or a decision was made. It was asserted that there are a relatively small number of key authoritative datasets currently available, and that these should be identified and disseminated.

DoD and Service capabilities. Some participants noted that a variety of organizations exist within the DoD complex for providing meteorological data, and the question was raised whether these capabilities could be harnessed to provide needed climate information. As an example, one participant pointed to engineering weather data (an example of climatic design parameters) developed by the U.S. Air Force's 14th Weather Squadron (14 WS), whose mission is to collect, protect, and make full use of authoritative weather and climate data to optimize military and intelligence community operations and planning. Among other uses, the data collected by 14 WS support design and construction of DoD facilities. An example of this is UFC 3-400-02 Design: Engineering Weather Data (DoD 2003), which describes the use of climatic design parameter data in planning, design, construction, sustainment, restoration, and modernization for all DoD projects. 14 WS has also increasingly received climate-related inquiries from staff on military installations with the desire to ensure that plans and processes include climate considerations when appropriate. As a result, in the past few years, 14 WS has begun to collaborate with several climate entities to address these needs. In 2014, 14 WS and the National Oceanic and Atmospheric Administration's (NOAA's) National Centers for Environmental Information (which is co-located with 14 WS) established the Climate Monitoring, Analysis, and Prediction (CMAP) capability to answer a DoD and Intelligence Community call for global climate-scale intelligence that could optimize long-term risk analysis and military decision making. In 2017, the 14 WS worked with the North Carolina Institute for Climate Studies in providing 50-year climate projection data for Langley and Thule Air Force Bases in order to facilitate MILCON cost-savings determinations for recently completed construction projects at each location. In support of DoD Directive 4715.21, "Climate Change Adaptation and Resilience" (currently under review), the Director of Air Force Weather has also established a Climate Plans Office that serves as a climate focal point for the Air Force and leverages operational climate services provided by 14 WS and other interagency partners.

There may be opportunities to leverage these efforts and other similar existing collaborations and capabilities within DoD to provide more continuously updated information. Notably, within the meteorological community, there is interest and opportunities to expand into the area of decadal (10+ years) climate modeling.

Another potential DoD source of installation-specific information on observations of both weather conditions and impacts is the installations themselves. On the one hand, in the context of discussion of "authoritative" sources of data, some practitioners raised concerns about having individual installations develop information to support design and planning. Others pointed out that many installations include meteorological stations and personnel, and there is potential to add capability for collecting and analyzing various types of *site-specific data* that would be useful (subject to proper coordination with leadership and clearance for public release). It was noted that at sites assessed in one SERDP research project (RC-2206), meteorological information was not collected for long-term analysis of changing conditions (Moss et al., 2016). For example, information on climate thresholds (points at which a system is disrupted or damages increase disproportionately) was unavailable. If thresholds could be documented, analysis of climate observations and model projections could be used to evaluate potential historical or future changes in occurrence. The question was raised (but not further addressed) of what would be technically and financially required to add capability to perform relevant analysis at selected installations. Installation collection of data on changes in damages, site utilization, and other potential consequences was also briefly discussed. It was noted that the Federal Emergency Management Agency (FEMA) and other groups have developed guidelines for collecting and integrating "disaster data" in hazard management and mitigation, and adaptation of these recommendations to high-priority DoD installations could improve understanding of evolving costs and adaptation planning needs (FEMA, 2015). Recent research focuses on the potential for cost-effective, post-event data collection through a variety of sources, including sensors, drones, social media, and others (McMullen et al. 2016).

Research community. Several participants raised the question of whether current U.S. research capability, e.g., the U.S. Global Change Research Program (USGCRP), was keeping pace internationally, and whether erosion of the U.S. national research program could create a security issue. For example, it was clearly stated that several areas of DoD would not be comfortable outsourcing analysis of observations and development of projections internationally. This led to suggestions from several participants that the argument needs to be made that erosion of U.S. capability is a substantial risk, and that support for USGCRP, the U.S. National Climate Assessment (NCA), and other activities needs to be increased in order to ensure that these programs address information needs of practitioners.

Finally, the role of the research community in meeting needs of practitioners was considered throughout the workshop and is discussed more extensively in the next section of this report, particularly current insights from the research community about whether "stationarity is really dead" and opportunities for future research. Here, we briefly note several comments from practitioners about "style" and format of information delivery. A commonly stated request from practitioners was the need to make information available more rapidly. Practitioners suggested that scientific information does not have to be "perfect;" rather what is needed is information (including analysis of uncertainty) that is "good enough" to support screening and ongoing planning/design processes, including application-oriented fact sheets, data sets, maps, scenarios, and other tools.

Participants noted that data through the Coupled Model Intercomparison Project (CMIP)[4] and other authoritative scientific activities is difficult to understand and access, and that much more attention needs to go into providing information that helps practitioners benefit from available knowledge of specific aspects of temperature and other atmospheric conditions, rainfall, wind speed, flooding, and compound hazards such as wildfire.

Finally, practitioners welcomed approaching development of a better working relationship with the research community (academic and government) through an ongoing dialogue focused on the needs of specific areas of professional practice. This issue will be addressed in the synthesis (final) section of this report.

[4] CMIP, organized by the Working Group on Coupled Modeling, serves as an important platform for the evaluation of climate models and the promotion of further development of climate models; data provided through CMIP is widely used in climate assessments.

3.0 RESEARCH ON NONSTATIONARITY OF CLIMATE AND RELATED ENVIRONMENTAL CONDITIONS

Scientists researching various aspects of physical climate, hydrology, coastal dynamics/ processes, and environmental risk assessment were asked to reflect during the workshop on the current state of science relevant to understanding nonstationarity and its implications. This section aggregates comments on several topics, including: (1) evidence to support the assertion that "stationarity is dead," (2) potentially viable methods for assessing nonstationarity, and (3) ongoing projects and research opportunities.

3.1 EVIDENCE ON NONSTATIONARITY

The assumption of stationarity enables anyone planning, designing, or engineering a fixed asset to assume that frequency, magnitude, intensity, seasonality, and attributes of climate (e.g., flooding) will be the same in the future as they have been over the past—often a 30-year climatological period. Any estimates in which statistical stationarity is assumed thus rest on analysis of observed climate conditions. For example, NOAA's Atlas 14 contains frequency estimates and associated confidence limits for precipitation for the United States by geographic sections.[5]

In response to a request from participants, a portion of the workshop was devoted to providing examples of analysis that establishes nonstationarity of different hazards/conditions in different locations. Analysis of recent observations and projections from climate, hydrology, and other models indicate the assumption of stationarity of future conditions can no longer be assumed to be valid, particularly with respect to extreme events. Shifts in extreme events, and hence identifying nonstationarity, can be described in several different ways, but they all fundamentally result in descriptions involving shifts or changes in probability distributions (see Figure 1, IPCC 2012, Karl et al. 2008). Changes in temperature and precipitation distributions, as well as related conditions such as increases in sea level, have been observed around the world, at scales from local to global.

[5] NOAA Atlas 14 is accessible here: http://www.nws.noaa.gov/oh/hdsc/currentpf.htm.

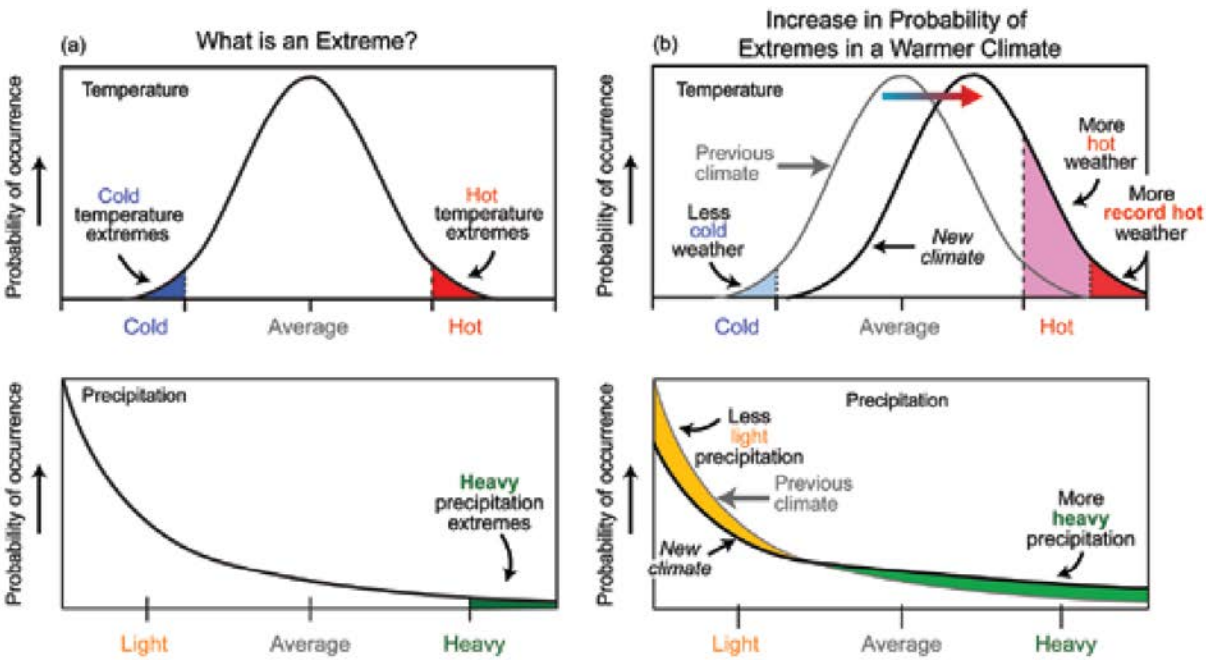

Figure 1. A Conceptual Illustration of What an Extreme Event in Temperature or Precipitation Looks Like, as Defined in Terms of a Probability Distribution of Events, As Well As How Shifts in the Distribution (i.e., nonstationarity) Can Result in Changes in Those Extreme Events

(Reprinted from Karl et al., 2008, Figure ES.1).

Much research discusses changes in mean and extreme precipitation and hydroclimate that are consistent with distribution shifts (e.g., Milly et al. 2008, IPCC 2012 and 2013). These shifts are underpinned by physical mechanisms: the Clausius-Clapeyron relation (as temperatures increase, the air's holding capacity for moisture goes up) leads to the hypothesized and observed process through which the most intense precipitation events will become more regular at the expense of moderate precipitation (see Figure 2, Held and Soden 2006, Karl et al. 2008). In combination with reduced snowpack and glacier coverage (e.g., Barnett et al. 2005), these hydrological cycle changes have further impacts on runoff, storage (soil moisture and groundwater recharge), and, hence, water management (Milly et al. 2005, Seager et al. 2007).

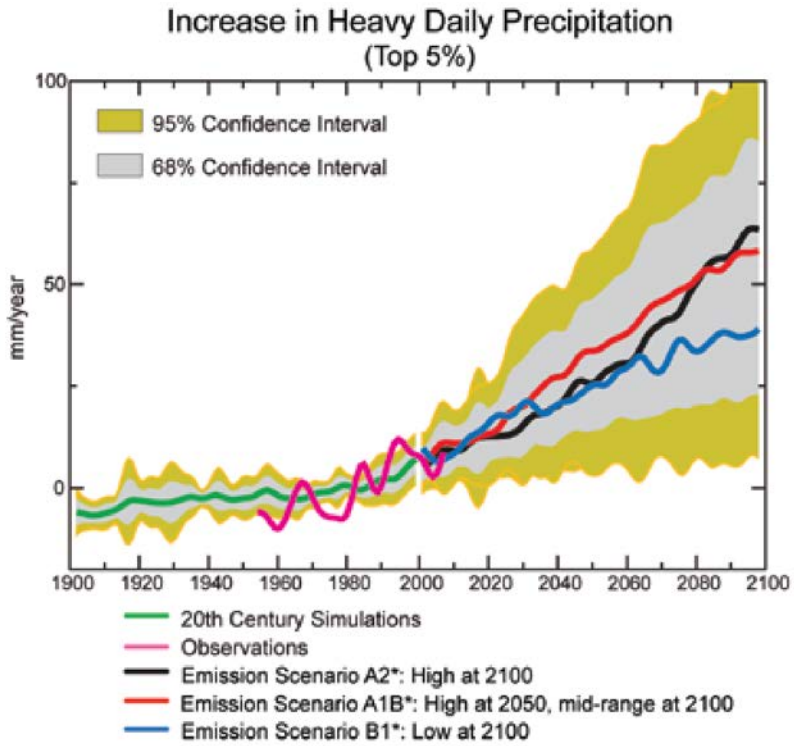

Figure 2. Observed and Modeled Changes in the 5% Heaviest Precipitation Events, as Compared to a Baseline of the Period 1961–1990.

Shading indicates the spread of models participating in the CMIP Phase 3 (Meehl et al. 2007, Reprinted from Karl et al. 2008, Figure ES.4).

Extreme temperature events are also showing evidence of distribution shifts. Many areas throughout the world are experiencing more frequent and intense heat waves and fewer extreme cold snaps (IPCC 2012). However, this conclusion does not hold universally. Regional analysis within the United States indicates increased heat wave intensity and frequency in some locations but not others (Kunkel et al. 2013). And some processes, e.g., increased variability of the position of the northern hemisphere polar jet (the popularized "polar vortex" phenomenon), are resulting in more winter intrusions of frigid Arctic air into the North American mid-latitudes (Hall et al. 2015, Francis and Vavrus 2015).

In some instances, assessments of nonstationarity may be insufficient for quantifying the most relevant risks. As an example, it is difficult to make broad global conclusions regarding changes in frequency and intensity of hurricanes due to climate change (Knutson et al. 2010). However, based on correlations between past storm surge and the temperature of the main development region for Atlantic hurricanes, one can conclude that storm surge from Atlantic hurricanes is likely to worsen in the future (Emanuel 2005, Webster et al. 2005, Grinsted et al. 2013). This information is useful statistically for design and planning purposes, in terms of the extreme conditions that must be weathered by installations. However, it does not provide more deterministic information regarding an individual storm's track, intensity, or duration. This information is essential for operational purposes, such as evacuations and emergency management, which have their own infrastructure needs (such as roads and access or redundancy of power generation and transmission).

3.2 METHODS FOR ASSESSING NONSTATIONARITY

From a mathematical standpoint, stationarity is a universally false assumption. However, such definitions are ultimately of limited utility; a more relevant question is whether situations are stationary "enough" that an assumption of stationarity is applicable when quantifying risks. This determination requires information about the risk tolerance of a particular asset or project. During the workshop, questions like this were raised in Panel 2 on information needed by practitioners (see workshop agenda in Appendix A). Panel 1 presented some ideas of methodologies for assessing shifts in distributions. One of the key outcomes of the interactions between Panels 1 and 2 was the highlighting of a disconnect between what practitioners need and what the scientific community can provide at present.

For example, standard methods among the scientific community for quantifying extreme events include quantifying changes in a set of indicators (e.g., Karl et al. 1999, Peterson et al. 2001), producing histograms of those indicators, and fitting them to generalized extreme value distributions (Kharin and Zwiers 2005, IPCC 2012). This procedure can in principle provide climatic design parameters that can be directly incorporated into design criteria (e.g., the probability of exceeding three inches of rain in a single day) and the design requirements for resilience to these events. In practice, obtaining accurate estimates that are useful for quantifying these design parameters can be fraught with difficulty and uncertainty, particularly when projecting decades into the future to understand the range of conditions that an asset may experience during its useful life.

Hawkins and Sutton (2009) usefully divide uncertainties in future projections into three broad categories, each of which has different relative importance depending upon the time horizon: internal variability, model uncertainty, and scenario uncertainty. Uncertainty due to internal variability is best described by the fact that while it may be difficult to predict any single event, the collection of events falls within a distribution. This source of uncertainty is present at all timescales and is the "truest" encapsulation of the concept of stationarity, in that it describes distribution shapes independent of how forcing (anthropogenic radiative forcing modulated by climate sensitivity) may alter those shapes (Figure 1 in Section 3.1). Hawkins and Sutton argue that it is the dominant source of uncertainty on shorter timescales, which ultimately describes issues with signal-to-noise ratios: observing a shift in a distribution either requires large changes or a long time to observe those changes, in addition to a well characterized baseline. In the medium term, the dominant source of uncertainty in projections is model uncertainty. This can include structural uncertainty (the model is missing processes that affect the results) and parametric uncertainty (the model has the relevant processes, but the best way to represent them may be unclear). We include in this category difficulties with downscaling, which we discuss later. The final category, which is the dominant source of uncertainty on longer timescales, is scenario uncertainty. This idea encapsulates the fact that predicting future climate is difficult, particularly when the range of potential futures is wide. For example, a future under Representative Concentration Pathway (RCP) 8.5 (no climate policy) is quite different from a future under RCP 2.6 (aggressive decarbonization).[6] Each of these sources of uncertainty hampers the ability to estimate nonstationarity.

[6] Representative Concentration Pathways, or RCPs, refer to four possible greenhouse gas concentration trajectories adopted by the Intergovernmental Panel on Climate Change for its Fifth Assessment Report (AR5) in 2014 (Moss et al. 2010).

As alluded to previously, regional downscaling is an important issue in projections of future conditions and can be a significant source of uncertainty. The purpose of downscaling is to take larger-scale model output and use it to provide finer-scale information, e.g., using global or regional models to describe what may happen at a particular installation. There are multiple commonly used methods for downscaling, but Kotamarthi et al. (2017) "cannot recommend a single approach even for the simplest of applications," meaning that each situation must be carefully evaluated to determine the most appropriate method to use that will aid in avoidance of introducing large biases; Ekström et al. (2015) provide some guidelines to this effect. As one workshop participant astutely stated, "Downscaling can be a great way to get wrong answers more precisely."

There are at present no universal methods for quantifying nonstationarity, particularly in ways that are useful for implementation in design criteria (Khaliq et al. 2006, Salas and Obeysekera 2014). There is need for work on how to best incorporate information about nonstationarity into scenarios and projections of future climate changes. There are some examples of attempts to do this, but no method has shown universal skill. Villarini et al. (2010) perform spline fitting (a purely statistical method), resulting in wide ranges of uncertainty in future projections. Using a slightly different fitting method, Villarini et al. (2009) obtained ranges of uncertainty that were too narrow. Silva et al. (2012) used non-parametric methods to assess nonstationary rates, resulting in degraded predictive ability. Kharin and Zwiers (2005) and Kharin et al. (2013) produced more reasonable prediction intervals, likely in part because of their reliance on physically-based representations (climate model projections) of future changes.

The area that has perhaps received the most attention is flooding. Flooding assessments are often site-specific (e.g., Rahman et al. 2013, Silva et al. 2012), which are often not generalizable and are only meteorological assessments, i.e., they do not take the next step toward being useful for planning purposes (e.g., Kharin and Zwiers 2005, Kharin et al. 2013). Another issue is understanding which indicators of flooding to use. Several studies have used discharge (e.g., Slater and Villarini 2016, Villarini et al. 2009), which is limited to areas with rivers. Some other studies use environmental variables (e.g., extreme precipitation, rain versus snow, soil moisture), which are tied to flooding but are not direct indicators of flood risk. Also of critical importance is the timescale of the variables that are being analyzed. For example, extreme precipitation requires high frequency output, whereas snow cover and soil moisture change comparatively slowly.

Given the challenges discussed, how can DoD best identify variables, regions, and timescales for which the assumption of stationarity is sufficiently invalid that a different approach than using estimates of past variability is required? A second challenge is then to provide definitive, quality-controlled estimates based on some other source of information (Milly et al. 2008, Lins and Cohn 2011). While there are no definitive answers to these questions, Sreetharan and Giovannettone (2017) provide several promising paths forward in the form of successful examples in which information about precipitation nonstationarity has been successfully translated into design standards. The examples they give include web-based tools to compute location-adjusted storm probability to design storm water management infrastructure and changes in 100-year floodplains. They also highlight the need for a unified approach to detecting nonstationarity in regionally refined areas—a prospect that seems elusive given current limitations in our ability to project future changes in climate, downscale them, and assess the degree to which those projections are nonstationary. Understanding changes in conditions at scales relevant for spatial planning, architecture, engineering, ecosystem management, and other practical applications is very challenging and involves careful analysis of observations and model results.

3.3 ONGOING PROJECTS AND RESEARCH OPPORTUNITIES

Participants discussed several ongoing research projects to test for nonstationarity and provide updated estimates of intensity, duration, frequency, seasonality, and other aspects of precipitation and coastal and surface flooding. This promise of a path forward in addressing these difficult yet crucial challenges is perhaps best highlighted by recounting some takeaway messages expressed by the participants, as well as some specific, high-priority research directions that were raised at the workshop:

- More research is needed on extreme events. To date, the focus of much climate science has been primarily on improving information on average conditions. However, the largest threats to infrastructure come from extreme events (e.g., storm direction, intensity, and duration). There are ample opportunities to improve our understanding of extreme events to reduce the risks they pose, as well as attribution of changes in the statistics of those events to better predict their probabilities (NAS 2016). A number of new methods are being developed and applied. How do practitioners understand and evaluate these disparate approaches to generating actionable information?

- Downscaling remains a crucially important yet elusive product of the scientific community. New advances in downscaling, such as the Localized Constructed Analogs or "LOCA" method (Pierce et al. 2014) are showing promise. The LOCA method is now the standard method in the NCA process for statistically downscaling climate projections of extreme events. There may be advantages to revisiting the topic of downscaling in a thorough, rigorous way to understand exactly for which situations, locations, and variables each method is most effective and the likely error magnitudes. An important point is that many methods of downscaling are more effective for mean climate features than extremes; some additional solutions are needed so that downscaling can provide information about risks to facilities. A number of participants noted the importance of complementary research on vulnerabilities and decision context to fill knowledge gaps that would limit the benefits of higher resolution information.

- Analogs may be a useful area of research for quantifying nonstationarity. For example, if future changes in Area A are projected to look more "like" present or past changes of Area B, perhaps information about meteorological statistics of Area B can be used to characterize the future conditions of Area A, which in turn can provide information about risks without requiring a long history of data to observe nonstationarity directly.

- In many situations, sites may face multiple sources of stress, and these stresses can interact or multiply. An example is how hurricane storm surge is exacerbated in the presence of sea-level rise. Understanding these interactions and having capabilities to model them is crucial for understanding the entire picture of hazards that a site may face.

- High latitudes are the sites of some of the most rapid climate changes on the planet. This includes water resources, which sustain essential ecosystem services. Changes in high-latitude water resources can be abrupt and difficult to predict. As activity in the Arctic increases, these essential systems and the additional strains placed on them need to be quantified so that available water resources can be understood and appropriately managed.

- A concern was expressed at the workshop for the need to have an updated, extended, and centralized authoritative database of meteorological information that can be used for planning and design. This climatic design parameter database would need to be easily and continually updated with the latest information. This information could be folded into a larger exposure database that, for each site, associates the relevant hazards, indicators/ variables that could be used to measure those hazards, important factors related to those hazards (e.g., frequency, duration, and intensity), and an estimate of the level of certainty. Such a database does not presently exist, but it could in principle be prototyped.
- There are two broad camps of practitioners: those focused on scenarios (i.e., particular visions of the future) and those who are more focused on risk and vulnerability decisions at specific locations. Weaver et al. (2013) argue that there is substantial room to improve the information contribution of climate models in both of these areas. There is a need for the scientific community to work more closely with practitioners, not only so the information that is provided is more useful, but also in terms of improving communication, particularly in a probabilistic framework.
- Much of the needed information could be produced by a robust private-sector enterprise that makes tailored products/services.
- In many cases, it may not be possible to obtain all of the necessary information to quantify design risks for infrastructure. In such cases, avoiding overdesigning will require an adaptive "learn-as-you-go" approach that automatically includes the capacity to adjust to changing conditions at all stages of design and construction, as well as long after the structures are built.

Example research needs drawn from the workshop are elaborated in Appendix C.

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4.0 SYNTHESIS PERSPECTIVES AND FUTURE DIRECTIONS FOR SERDP/ESTCP

A closing synthesis session focused on ways to provide needed information for practitioners that take advantage of the current state of science and present opportunities to improve our understanding of relevant climate and environmental systems. Comments addressed both community-wide issues and ideas for SERDP/ESTCP. One general point was to invite and facilitate the coordination of the many professional associations and groups (such as ASCE and AIA) to work with SERDP/ESTCP, as these groups are currently working to develop methods and standards appropriate for nonstationarity. Major perspectives included the following:

Need for continued dialogue: Practitioners, the science community, and decision makers agreed on the need to convene a topically-focused set of workshops and meetings to develop targeted Communities of Practice to define questions and information needs, identify relevant uncertainties, specify options for managing potential consequences, and frame needed research. In addition to developing a shared understanding of the challenges and available information base, these workshops are seen as essential to framing research that will have relevance to the decision context and options being considered in planning and design. SERDP/ESTCP were seen as playing an important role in convening workshops focused specifically on DoD design challenges. Other suggestions that could be explored and would support this objective include developing a "lexicon" and other tools to improve communication among scientists, engineers, architects, planners, and other users; improving approaches for identifying and characterizing confidence and uncertainty and providing better graphical representations of uncertainty that are useful in decision-making processes; and developing projects that fuse climate science, design, and decision sciences methods in the context of current DoD/Service processes for planning, operations, and management.

Process suggestion – encourage "end-to-end" proposals: SERDP could help close the gap between research and practice and encourage "co-production" of use-inspired fundamental research by giving favorable consideration in its research solicitations to proposals that include (1) fundamental science, (2) application, and (3) evaluation of utility in each proposal. Other research funding agencies such as the National Science Foundation have adopted this approach, and anecdotal evidence suggests it incentivizes and encourages more effective collaborations.

Near-term win – improving delivery of initial products: There is an opportunity to improve availability of data and information for practitioners by accelerating analysis of observational and model archives to extract information about the most likely conditions and extremes for specific hazards. SERDP/ESTCP could play a useful role in solidifying understanding across different areas of DoD regarding the hazards, return intervals, locations, and specific metrics (determined by needs of different professional areas of practice). These ideas could then be used to frame Statements of Need around specific hazards. Several example research needs were described at the workshop and are listed in Section 3. Several are framed as examples in greater detail in Appendix C. Community of Practice workshops such as those described in the point above about the need for continued dialogue could help define these needs for the research community members who can tap available findings, improve analysis of uncertainty, and frame new studies. This should not be a long, drawn-out process. Specific suggestions for these products are mentioned in Sections 2 and 3 of the report.

Longer-term objective – reframing the problem as a risk management challenge: A second broad priority that would improve practice, but that requires both technology transfer and new fundamental research, is developing methods and data to support incorporation of risk management principles into management of nonstationarity in planning and design. There is a current impasse between physically-based models of climate and environmental systems that have been observed in the literature (e.g., Montanari and Koutsoyiannis 2014) that are not effective for uncertainty characterization and statistical analysis, and statistical models used in planning and design. Some steps need to be taken by the practitioner community including mainstreaming risk-based methods into technical bulletins, manuals of practice, and design criteria. This involves reframing the issue posed to climate and environmental scientists from "tell me what's likely to happen" to working with scientists to identify robust combinations of scenarios and infrastructure options. However, the research community also needs to embrace the production of information that supports risk management. Some additional ideas that could accelerate reframing around risk include:

- Conducting decision-framing research that uses established cost or performance-related metrics to identify climate and other environmental information needs, including approaches for analysis of spatial distribution of sensitivity and adaptive capacity;
- Development of economic and other practical metrics of impacts and consequences; or
- Conducting screening-level assessments that focus on mission importance, sensitivity, and adaptive capacity that can be used with improving information on hazards to systematically set priorities for areas where planning and design of infrastructure needs to consider nonstationarity.

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APPENDIX A WORKSHOP AGENDA

Pacific Northwest
NATIONAL LABORATORY

Non-Stationary Weather Patterns and Extreme Events:
Informing Design/Planning Applications for Long-Lived Assets
Joint Global Change Research Institute (3rd Floor, Room 3502)
June 29, 2017

AGENDA

0900	Welcoming remarks from the Joint Global Change Research Institute
0910	Round robin introductions
0920	**Context setting: DoD and SERDP/ESTCP**
0930	**Workshop overview and objectives: informing planning, architecture, and engineering**
0935	**The science basis: Is stationarity really dead?**
0945	**Assessing the changing nature of coastal risks**
0955	**Adapting infrastructure and civil engineering practice to a changing climate**
1010	Discussion
1030	Morning Break
1045	**Panel I. Environmental processes and exposures: frontiers of Earth system research**
1145	Working Lunch
1245	**Panel II. Practitioners: information needs**
1415	Afternoon Break
1430	**Panel III. Synthesis and perspectives on research needs**
1530	**Takeaways and elements of a research plan: next steps**
1600	Adjourn

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APPENDIX B MOTIVATING QUESTIONS FOR WORKSHOP PANELS

The following memo was distributed to the workshop participants with the agenda prior to the workshop. The memo describes the purpose and workshop organization, and offers questions for consideration under each panel.

Motivating Questions for Workshop Panels

Overall purpose of workshop: assemble a preliminary assessment of the current state of practice in design and planning long-lived assets and infrastructure in an age of nonstationary environmental and climate conditions. We will draw on current practice in DoD and the military services, other federal agencies, the private sector, and professional associations that set standards and professional practice. During the workshop, we will focus on four broad questions:

1. For which assets/infrastructure is it most important to consider the potential implications of nonstationarity on effectiveness, lifespan, costs of operations/recovery, and other factors?
2. For those areas where nonstationarity is an important consideration, which areas of practice are successfully addressing the issue, and how is progress being made?
3. From an environmental and Earth system science perspective, for which exposures (to climate stresses/extremes) or "loads" is progress being made in improving representation of nonstationarity and delivery of information to practitioners in engineering and planning professions?
4. What are the research and assessment priorities for increasing understanding of vulnerabilities and improving methods/information/decision frameworks that will increase resilience (reduce impacts, speed recovery, lower costs, enhance safety, etc.)?

The bulk of the workshop is organized into three panels, each of which will include a set of panelists offering short observations (~5 minutes) and open discussion. Participants should raise any issues they believe to be relevant. We offer several potential focus questions for each panel to suggest topics to consider:

Panel 1: Earth system and environmental processes and exposures

- Based on your experience, describe an area of climate/environmental science that is examining the validity of the stationarity assumption; if that assumption is violated, how is nonstationarity analyzed and what products/outcomes/benefits to engineering/planning practice are likely to result? (yes, this is an invitation to advertise current areas of research)
- For which exposures/variables/processes beyond the one you describe are we confident that progress could be made given current or emerging state of science—in other words, where are the scientific opportunities to provide improved information?

Panel 2: Engineering and design practice: priorities, current practice, and progress

- For which assets/infrastructure is it a priority to consider nonstationarity, and what criteria have you used to reach that decision (e.g., mission importance, recent occurrence of exposure, potential cost savings, …)?

- In your area of practice, is nonstationarity being considered, and if so, how? (progress could be represented by updated standards/planning processes, improved information on environmental loads/exposures, improved methods for costing, use of scenarios in planning, updated policies, and others)
- Are you familiar with other areas of engineering or planning practice that are making progress, and can you briefly describe these and point the project team to additional references or follow up contacts?
- What exposures/variables/environmental processes/tools are of greatest importance?

Panel 3: Synthesis perspectives

- How well defined are information and decision support needs for engineering/planning practice, and can you point to reports or studies that set forth these needs?
- What ideas do you have of ways to *improve practice*, for example updated standards, uncertainty characterization, costing methods, guidelines on definitive information sources and their use, …, to take advantage of currently available information?
- What ideas do you have to *improve the scientific information* base for design processes, for example by focusing on understudied hazards/loads, providing information at higher temporal or spatial resolution, or other innovations?

APPENDIX C RESEARCH CHALLENGES AND OPPORTUNITIES FOR SERDP/ESTCP'S RESOURCE CONSERVATION AND RESILIENCY PROGRAM

Ideas from a Workshop on Nonstationarity Weather Patterns and Extreme Events

Ideas for potential research opportunities stemming from the workshop on *Nonstationarity Weather Patterns and Extreme Events: Informing Design/Planning Applications for Long-Lived Assets*
on June 29, 2017

An informal collection of white papers prepared by Richard H. Moss, Ben Kravitz, and Alison Delgado

Pacific Northwest National Laboratory

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Preface

These ideas for research were inspired by discussion at a small workshop on *Nonstationary weather patterns and extreme events: Informing Design/Planning Applications for Long-Lived Assets* on Thursday, June 29th at the Joint Global Change Research Institute (JGCRI) in College Park, Maryland (http://www.globalchange.umd.edu/). This meeting was convened with the Resource Conservation and Resiliency program area of the Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP) (https://www.serdp-estcp.org/) to explore how environmental science (including models of hydrology, ecology, health, climate, and decision making) could better inform decisions regarding long-lived infrastructure important for Department of Defense (DoD) missions.

Participants in the workshop included: (1) "practitioners" (engineers and planners from within DoD, the military services, and other government agencies); (2) researchers specializing in environmental, Earth, and human systems; and (3) program managers from DoD and other agencies (with either research or operational/mission/budgetary responsibilities). During the meeting, participants reviewed the state of science and application within several areas of practice important to DoD.

Throughout the workshop, participants identified several possible research needs and opportunities. Based on those discussions, a few of us (Moss, Kravitz, and Delgado) drafted a series of short white papers to suggest possible general areas of research, not to propose specific research projects. These white papers are contained within this appendix. While participants in the workshop were given the opportunity to comment on the write-ups, responsibility for the content lies with the PNNL team.

This appendix contains nine sections. Sections 1–8 of Appendix C identify a series of promising environmental research directions that we envisioned could serve SERDP/ESTCP program needs. Because they were inspired by comments made during the workshop, their content has a heavy (but not exclusive) focus on nonstationarity and risks to infrastructure. The white papers identify user requirements, areas of progress, remaining research, and application needs. Section 9 describes a number of ideas for *how* to conduct research at the boundary of practice and fundamental science. These ideas are at least as important as the possible topics themselves and could also be reflected in future statements of need.

We note that there were additional ideas raised during the workshop that we have not had time to explore as potential future program ideas. In some cases, SERDP/ESTCP leadership is not needed because DoD can build on fundamental science conducted by other agencies. In other cases, the topics may require an approach that lies between traditional SERDP scientific research and ESTCP technology transfer – research on how to use a particular scientific insight in applications that precedes technology transfer. Some of these additional topics potentially relevant to SERDP/ESTCP include:

- Research focused on improving projections of storm direction, intensity, and duration;
- Continued work to apply, evaluate, and improve scenarios and other tools for projecting interactions of sea-level change, storm surge, precipitation/land-based flooding for particular sites, building on work at the National Oceanographic and Atmospheric Administration (NOAA) and other agencies;

- Development of tools and a “lexicon” to improve communication among scientists, engineers, architects, planners, and other users;
- Research on materials fragility and implications for infrastructure/building design;
- Development of economic and other practical metrics of impacts and consequences;
- Projects that fuse climate science, design, and decision sciences methods in the context of current DoD/Service processes for planning, operations, and management;
- Improved approaches for identifying and characterizing key uncertainties and providing better graphical representations of uncertainty that are useful in applied settings.

A common theme in all the white papers is that there are remaining challenges in connecting scientific research with the needs of DoD decision makers and users. We envision that resolving this gap could be accomplished through a continuing dialogue among users, the research community, and managers/decision makers. We see an opportunity for SERDP/ESTCP to play a central, catalytic role in this regard.

We thank SERDP/ESTCP for its support and collaboration.

Richard Moss (PI)

Ben Kravitz

Alison Delgado

1. Quantifying the effects of nonstationarity through analogs

Nonstationarity describes the process by which the distribution of climatic events in a particular region or sector shifts as a result of overall changes. This can result through shifts in mean climate or changes in the distribution shape (Figure 1-1; IPCC, 2012), but the net result often involves changes in the intensity or frequency of extreme events. These shifts are crucial to understand, as they determine how well the past can be used to predict the future, particularly with regard to low probability, high consequence events, or maintenance of conditions that affect training activities and/or management of test/training ranges and other infrastructure that require conditions within specified thresholds (Moss et al., 2016).

Despite its importance, nonstationarity is difficult to quantify. Recognizing changes in distributions requires long observation times to obtain sufficient statistics. As an example, changes in the frequency of 1000-year floods are difficult (or impossible) to observe over periods of several decades, yet understanding whether 1000-year floods will begin to occur every 10-20 years is a crucial piece of information for infrastructure managers. Even with long time series of data, statistically insignificant shifts in distributions can have serious practical effects.

Here, we describe a research idea to approach assessments of nonstationarity in terms of analogs. An example of this could be the distribution of precipitation events in a region undergoing desertification. While it may be difficult to observe shifts in the distribution of precipitation events in that region, one can use knowledge that the region being studied is going to become more "like" a desert region. As such, it may be possible to use observations of the distribution of precipitation events in a desert region to understand what the distribution might look like in the region of interest.

To some extent, this idea has been explored in terms of Köppen climate classes (Kottek et al., 2006). Each of these classes has typical profiles of behavior, so evidence that a region is shifting from one class to another gives some indication as to what the climate may become. However, this belies two immediate questions related to quantification and scale. As to the first, one needs metrics of shifting: how can one measure that a region "is beginning to look like" another region or another climate? Is it sufficient to measure shifts in mean climate or the occurrence or intensity of extreme events? A second consideration is the spatial and temporal scale that is necessary to observe and report changes. Is it important to observe fine-scale changes to best quantify the risks to a particular site or area, or is it sufficient to observe broad regional trends? How much downscaling is needed to gain an accurate assessment of a site? Many assessments (like Köppen classes) deal with large swaths of land that evidence typical patterns of conditions – when is that sort of approach sufficient, and are there options for bringing in local variations that could affect conditions at the fine scales that DoD applications will typically require?

A statement of need could elicit proposals to address these questions. Initially, the focus could be on the stressor of heat waves, due to its clear signal and importance, the difficulty of detecting and quantifying changes in temperature distributions, and the known ties between mean and extreme temperature. A case study could address the following:

- What is the relationship between mean temperature and heat wave frequency or severity as revealed in both historical observations and climate models? How heterogeneous are those relationships?
- How have those mean changes shifted in the past? Have any regions become more "like" other regions in terms of mean temperature, and do temperature extremes shift accordingly? At what spatial resolution are these relationships still valid?
- Using these relationships, what do model results say about risks from temperature extremes under different future scenarios? To what degree is downscaling of these results needed to produce meaningful information that can inform training schedules or management of test/training ranges or built infrastructure (all of which require conditions within specified thresholds)?

Once these relationships are established, other exposures could be explored, as well as the ability to translate lessons learned from heat waves into other exposure types.

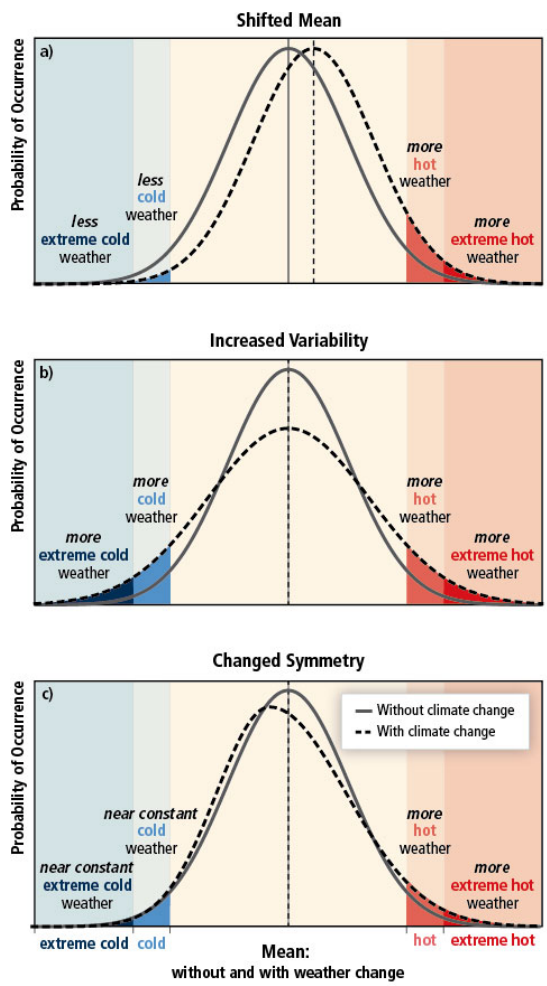

Figure 1-1. Illustrations of How Extreme Event Frequency Can Change Via Shifts in Distributions of Temperature. (Figure 3 from IPCC, 2012.)

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2. Planning and design risk mitigation through continually updated engineering weather databases

The term *engineering weather data* (often referred to in the main body of the workshop report as climatic design parameters) describes the likelihood of certain environmental conditions in a particular locale, such as temperature, precipitation, and wind speed, that are part of the operating envelop of conditions required for safe operation and/or of infrastructure, testing, training, or other activities. This information is essential for planners, designers, and facility managers to understand the conditions that infrastructure is likely to face so that some of the most important environmental risks can be mitigated. As a crude example, a building in Miami requires resilience against hurricane-force winds, but planners need not take into account snow load on the roof.

Nonstationarity of climate becomes problematic for these planning and operational concerns because rare events (e.g., extreme heat or rain) can become more regular, and relatively unseen events (e.g., 1000-year floods) can become real risks to infrastructure. As conditions no longer reflect those under which existing infrastructure was designed, at what point is it too risky to continue to operate existing infrastructure without extensive retrofitting? In the case of previously unseen events becoming real risks, infrastructure is not likely to have been planned to withstand those events because they were considered too rare, whereas that may no longer be true under a changing climate. Planning for an increase in frequency of extreme events is certainly possible, and it can be costly (although not necessarily so). Planners need to understand how environmental risks are shifting and how they are likely to shift in the future so that design criteria can take into account the likely conditions over the next several decades.

These decisions need to be made regularly and on site-specific bases so practitioners can make informed decisions about costs, probabilities, and consequences to critical infrastructure. Most existing compilations of such engineering weather data are based on old information (i.e., implicitly assume stationarity), so their quantifications of risk may be out of date. A statement of need could elicit proposals to revitalize and automate this process so that practitioners can have the most up-to-date risk quantification available.

This process could include some of the following components:

- Identify standards for design and operation parameters, as well as probabilities of extreme events based on historical data (i.e., under the assumption of stationarity). Quantify the annual frequency of occurrence for key variables (e.g., the probability of a day exceeding 100°F is 5%).
- Develop data streams for each of these design standards, quantify their accuracy, and describe how frequently these data streams should be updated (given the value of the updated information and costs to produce it).
- Collect and disseminate data and design a process for periodic updates with the latest information on probabilities of extreme events.
- As an experimental product, provide projections of how those probabilities are likely to change under different (likely downscaled) scenarios of future climate and weather conditions.

3. Improving predictions of severe storms using deep learning

Increasing severe storm forecasting accuracy and warning time will prevent damage to life and property and support better design standards. Intensity, frequency, and duration of extreme storms, such as mesoscale convective systems (MCSs) are expected to change in the future (e.g., Kendon et al., 2014); understanding these changes is crucial for decision makers, particularly in terms of infrastructure design, facilities operation, and emergency response. We need to better understand the conditions under which storms form, how they are likely to evolve, and the paths they are likely to take.

At the most basic level, understanding severe storms requires tracking them to observe their paths. Current storm tracking methods are adequate for "ideal" cases (e.g., isolated storms), but prone to errors for complex storm events (e.g., merging storms), resulting in "jumps" in storm tracks and occasional failures when tracking particular storms. These failures lead to uncertainty in the overall statistics, limiting the applicability of the tracking for certain applications (Feng et al., 2011).

Another important consideration is understanding the environmental conditions surrounding storm genesis, intensification, where the storms will move, and when they will dissipate. Relationships between key meteorological variables (e.g., daily temperature maximum and ambient humidity, instantaneous wind speed), as well as climatic variables (e.g., changes in average temperature or humidity), and storm characteristics are not well quantified, hampering storm predictability. This is further complicated by the issue of soil moisture "memory." As precipitation from a storm falls, some of that water gets stored in the soil, altering surface moisture and energy fluxes to the atmosphere, hence affecting the environmental conditions surrounding subsequent storm genesis (e.g., Taylor et al., 2007). This "memory" of storm tracks is well known over oceans, where hurricanes leave cool tracks in the upper ocean layers that can dampen subsequent storms. However, the effects of memory over land are unclear, partly due to the complexity of soil and vegetation, as well as the inherently noisy nature of land precipitation.

A statement of need could highlight improving understanding and predictive capability of extreme flood-producing storms, focusing on MCSs over the U.S., specifically in the context of infrastructure design, facilities operation, and emergency response. There are many potential approaches to addressing this problem, including improvements in traditional tracking algorithm approaches (e.g., Feng et al., 2011), modeling and data assimilation techniques to forecast storms, and "deep learning" methods on training data (satellite imagery and measured precipitation amount, combined with high resolution model simulations over CONUS) that are used to train a convolutional long-short-term memory (LSTM) network (e.g., Shi et al., 2015). Whatever method is used, it must be able to capture correlations and evolution of behavior in both space and time simultaneously, while preserving any nonlinear relationships in the data.

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4. Prototyping an exposure database

Assessing exposure risk to various aspects of DoD mission space is the first step in identifying critical research needs for reducing or managing uncertainty in dealing with those exposures. Each exposure at a particular site or in a particular region has numerous attributes, each of which will affect the overall risks presented. Planners and installation managers who wish to quantify risks from exposure need all of this information, including the likelihood of occurrence of particular exposures, what their potential consequences are, the state-of-the-art knowledge regarding uncertainty in that exposure, how to reduce or manage that uncertainty, and how much that would cost.

One research idea is to prototype a database for a select number of exposures that contains the relevant information needed for planners, installation managers, and decision makers. With this information in hand, they will be well positioned to make decisions that reduce risks to their mission from environmental factors.

Such a database could contain a nested hierarchy of levels and a sufficiently intuitive user interface that little specialized knowledge would be required to use it. Figure 4-1 provides a schematic of the sorts of information this database could include for a given DoD site "exposure database."

As an example, for the first level in the database, one site in the Midwest United States may be exposed to droughts, floods, heatwaves, and winter storms, but will not be concerned with sea-level rise. (There is experience with this sort of screening-level approach, for example, using the example of Hall et al., 2016 for sea-level rise or the U.S. Climate Resilience Toolkit available at https://toolkit.climate.gov.) At the next level (i.e., for each exposure) is a list of relevant climate- and weather-related variables. For example, if the exposure of concern is drought, some relevant variables could include daily minimum and maximum temperature, precipitation, soil moisture, and a vegetation index. For temperature, metrics of interest can include wet bulb globe temperature or cumulative heating and cooling degree days. The subsequent level would be information pertaining to each variable:

- spatial extent (e.g., how widespread elevated temperatures are)
- temporal extent (how long temperatures have been elevated, how often this happens, and whether it happened during a particularly vulnerable time)
- magnitude (a heat wave with temperatures exceeding 120°F has different consequences from a heat wave with temperatures around 100°F)
- whether there are any compounding factors (is only temperature elevated, or does the elevated temperature coincide with a long period of no rainfall)

The next level of the database could consist of estimates of uncertainty associated with each of these factors and the sources of those errors: nonstationarity, scenario divergence, model uncertainty, observation uncertainty, and internal climate variability. At this point, the database could have links to different data sources that possess all of the attributes of the decision tree; in effect, this database provides a hierarchical search through the metadata of each dataset, enabling the user to select and understand the available data.

Initially, this database could be prototyped for the single exposure of heat waves to understand some of the details as to how such a database would be constructed in practice and to resolve user interface issues before it is fully populated. The benefit of starting with this exposure is that temperature is well observed at all potential sites across the United States (i.e., confidence in the data is high), and one can unambiguously define metrics for heat waves. The more complicated cases involving sparse data or low confidence in observing ability could be addressed at a later point so as not to interfere with the initial efforts.

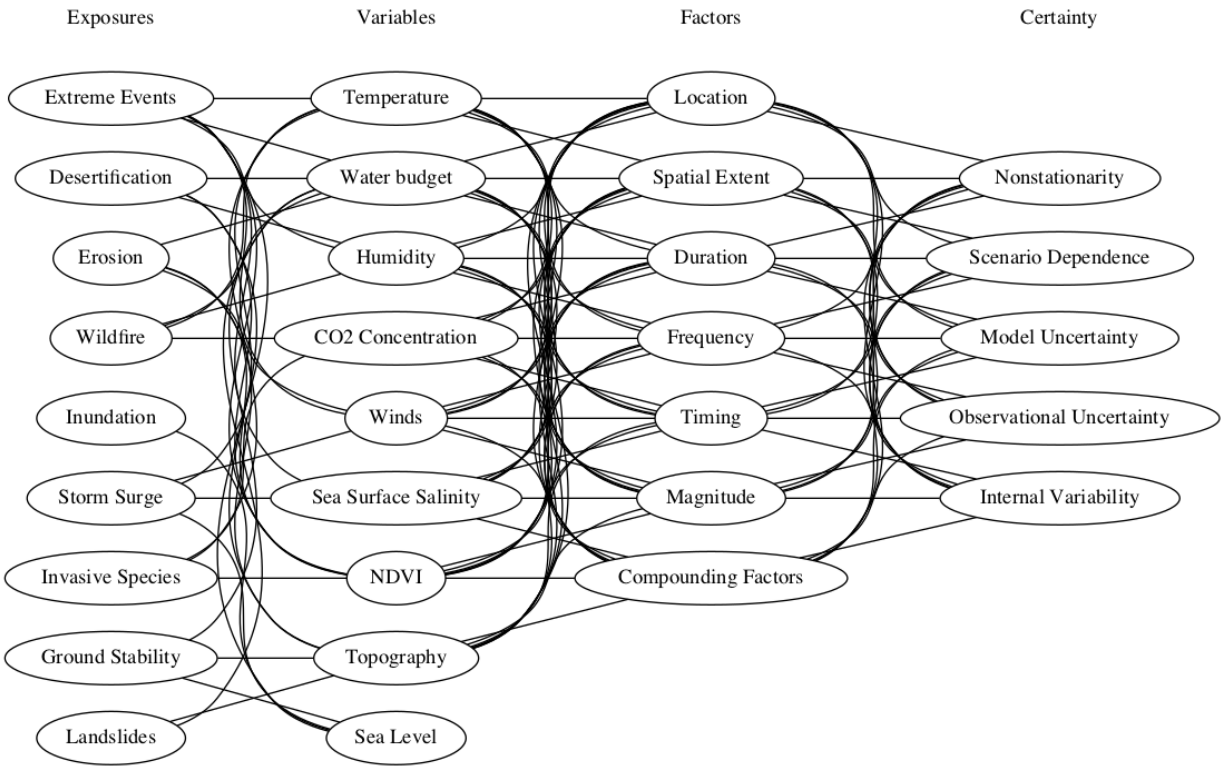

Figure 4-1. A schematic of the information that a database might contain, including exposures applicable to a particular site, a list of variables that apply to each exposure, important factors including the spatial and temporal extent of changes in those variables, and a metric of the certainty (or lack thereof) in our knowledge of each variable.

Reference

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5. Quantifying high-latitude water resource changes

High latitudes are the sites of some of the most rapid climate changes on the planet. This includes water resources, which sustain essential ecosystem services. Changes in high-latitude water resources can be abrupt and difficult to predict (e.g., Trenberth et al., 2007). As activity in the Arctic increases, these essential systems and the additional strains placed on them need to be quantified so that available water resources can be understood and appropriately managed.

At present, changes in high-latitude water systems are difficult to observe and predict. The remoteness of these areas makes ground-based observations difficult to obtain, and orbital geometry prohibits many satellite instruments from collecting fine-scale, space-based observations at high latitudes. As such, key observations necessary for understanding the hydrological cycle are missing, including fine-scale digital elevation maps (DEMs), precipitation amount and phase, and permafrost melt (e.g., Serreze et al., 2000). There is a clear need for methods of "filling in" any missing data.

In the case of missing data, traditional approaches would involve pursuing additional observation campaigns; this may not be feasible for many of the sites where information is most needed. A promising research idea is understanding whether there are methods of producing synthetic data with the appropriate spatiotemporal structures. This could involve a variety of methods, including the use of deep neural networks, trained on data taken from similar, more easily measured areas (e.g., snow-fed watersheds), to provide information for the region of interest. The field of interpolation has a long history, with both agnostic (i.e., just using the data that is available) or parametric fitting (e.g., incorporating a model or observations from analogous situations to provide some additional information regarding the expected data structure). Recently, deep learning approaches have shown promise in interpolating sparse data in other fields while retaining patterns of spatial and temporal correlation (e.g., Ronzato et al., 2007).

Even if data is not missing, the relationships between water resources and that data are not entirely clear. In such instances, there may be opportunity for a data driven modeling approach, whereby hydrological models are driven with observations to uncover these relationships. This area includes additional research opportunities, such as which models are most appropriate, how often the data should update the internal model state, and the minimum data requirements (frequency and resolution). Important steps in this activity would be to quantify sensitivity to errors and validate both the datasets and the modeling approaches.

There are many existing datasets that could support this effort. A fine-scale DEM has already been released for Alaska, as well as tools to analyze features in the DEM (NGA, 2017), and there are plans to construct such a DEM for the entire Arctic (North of 60°N). Also available for Alaska is the Scenarios Network for Alaska and Arctic Planning (SNAP, 2017), which provides 2-km resolution downscaled precipitation from five general circulation models. More broadly, the PRISM climate group provides similar resolution temperature and precipitation data for the United States (PRISM, 2004). The Global Terrestrial Network for Permafrost is exploring efforts in data fusion to understand relationships between permafrost melt and thickness of the active layer (GTN-P, 2017).

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6. Establishing common practices in the infrastructure risk assessment community

Assessing risk to infrastructure is a common practice for a wide variety of agencies, sectors, and facilities. To a large extent, these practices are individualized, i.e., there is no overarching common practice for risk assessment. Furthermore, while there are numerous design, planning, and management practitioners, there is little evidence of a broader community except for within certain sectors (e.g., environmental risks to transportation).

One idea that emerged from the workshop was to develop a means by which a "community of practice" can be developed for the purpose of establishing shared methods for infrastructure risk assessment. By "community of practice" we mean a group of end users and scientists engaged in the challenge of managing infrastructure risk over multi-year/decade time frames when past practice is not a reliable guide for the future. A community of practice must promote effective communication and collaboration within and across projects and overcome impediments to collaboration such as different vocabularies/epistemologies, feelings of competitiveness, time pressures, and other factors.

One possible approach is to target already well-established communities, for example water resource management and transportation. A statement of need could elicit proposals for a series of workshops and related stakeholder engagement exercises that would provide a forum for discussions between the two groups to identify commonalities and differences in exposures, how those exposures can be quantified (environmental variables and spatiotemporal variability), and current practices among the two communities for assessing and mitigating risk. Desired outcomes from proposed responses would identify whether there are common practices that can apply to both communities, as well as areas where practices must be sector-specific. Another objective could be to document the process by which these two areas interact and develop common practices. This will aid in providing a methodology whereby different sectors can interact to form a broader community around infrastructure risk assessment.

There have been several efforts to pursue a community of practice on a local level. The California AB2400 activity has set up a task force to accomplish exactly this for the state of California. New York recently completed their process in doing the same. Canada has produced a report documenting its attempts to create a nationwide community for assessing infrastructure risk. There are many opportunities for collaboration to conduct a meta-study of these different efforts and ascertain best practices that show clear promise for the United States or the international community.

7. Scenarios for design and planning of long-lived infrastructure

Scenario analysis is a useful tool for understanding the strategic implications of environmental risks and opportunities. Scenarios can be defined as coherent, internally-consistent, and plausible trajectories of future states of the world, which may be quantitative, qualitative, or both (Carter et al., 2007). They have their roots in U.S. military planning and gaming (when Herman Kahn pioneered *future now* thinking after World War II[7]) and are broadly used for analyzing strategic decisions with long-term consequences. Though definitions of scenarios can vary depending on their use, there is wide agreement that scenarios are not predictions about the likelihood of any particular set of events occurring in the future (Moss et al., 2010). Rather, scenarios are possible future outcomes, and hence useful in addressing questions about uncertain future conditions and their implications.

Here, we describe a research need to explore the development and use of scenarios for planning and design of long-lived infrastructure exposed to future changes in the frequency and duration of extreme weather events. There is a critical need to rethink the design and planning process to ensure investment in long-lived infrastructure considers the challenges of nonstationarity. In general, infrastructure has a lifespan of at least 20 years; therefore, most existing and planned infrastructure will still be in use by 2050 when changes in average weather patterns and extreme events might have far more significant impacts than they do today. It is less clear how and when all of these changes will occur and with what intensity they will affect the local level. Scenario analysis could be useful to address some of these uncertainties.

Although DoD has a long tradition of using scenarios to inform strategic thinking, there is a lack of scenarios at the spatial and temporal scales needed by DoD personnel for informing decisions related to infrastructure design resiliency to future environmental impacts. Changing weather patterns and extreme weather events are a global phenomenon but its impacts are local, thus making planning and adaptation particularly challenging. The inherent uncertainties related to projecting impacts are numerous, starting with assumptions about population and technological changes, for example, to decision making on a local scale. Most impacts, vulnerability, and adaptation assessments rely on two sets of scenarios developed in parallel: the climate-related "Representative Concentration Pathways" (RCPs) which capture a range of plausible total radiative forcing in the year 2100 relative to 1750, and the "Shared Socioeconomic Pathways" (SSPs) which focus on socio-economic challenges to adaptation and mitigation. Both the RCPs and SSPs, which were generated for the assessments of the Intergovernmental Panel on Climate Change, are useful for cross-country analyses, but become unreliable for assessments at local scales. Moreover, scenarios that are available at finer scales are generally only useful for a specific location or question, and are not suitable for other applications.

A statement of need could elicit proposals to develop a flexible framework for integrated scenarios focused on the nexus of extreme weather events and infrastructure impacts. Integrated scenarios are an attempt to coalesce multiple interdependent physical and human dynamics (e.g., climate, population and demographics, and land cover and use) in a consistent matter. Mahony (2016) describes integrated scenarios as scenarios that structure thinking about the future, bound uncertainty, document important assumptions, help communication, widen perspectives, and allow exploration of qualitative drivers in development paths such as social and institutional drivers. These

[7] Ringland, Gill, Scenario Planning, John Wiley 2006 (2nd ed.)

sorts of scenarios are essential for supporting cost/benefit analysis and development of management-oriented metrics to avoid over or under designing infrastructure.

This research activity could have the following major components:

- Assessing the use of recently released climate, sea-level rise, and land-use scenarios by the U.S. Global Change Research Program for use in the upcoming Fourth National Climate Assessment.[8] Other relevant efforts such as the sea-level change and extreme water level scenarios developed for DoD by the Coastal Assessment Regional Scenario Working Group (Hall et al. 2016), and U.S. Geological Survey's simulated winter storm scenario ARkStorm (Porter et al. 2011) could be explored.
- Drawing from case studies at DoD and services to identify uncertainties in infrastructure design and planning assessments. DoD officials deciding whether to invest in long-lived infrastructure will increasingly require insights into driving forces of change and potential future evolution. A major question they will need to address is: in the long run, will the planned infrastructure be able to deliver the level of services it was intended for? Any decision to commission new or retrofit and repair extant infrastructure will need to address uncertainties related to future extreme whether events and other interlinked changes to be economically sound and ensure that the plans align with DoD mission. This leads to a second question: what are these uncertainties? Among some of the information that this activity could examine are scales of interest, what constitutes high stress for the systems being analyzed, and criteria variables that could be used to assess the importance of the stressors (e.g., cost, disruption in service, reliability).
- Developing a framework for scenarios of future conditions pertinent to infrastructure design and planning at DoD. The framework could be designed to provide self-consistent sets of information that frame uncertainty in key variables to DoD infrastructure design and planning. This activity might focus on development of a flexible framework that bounds projections of a core set of variables associated with low and high stresses for a selected set of coupled systems (e.g., land use and water systems). This is in distinction to previous scenarios that contain detailed "storylines" (narrative descriptions of possible futures) and associated detailed quantitative projections that limit their use for multi-scale analysis.

The process would also benefit from incorporating a participatory approach to encourage understanding for both managers and scientists and to clarify the challenges that subsequent decision making should address.

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8. Screening-level assessments

A challenge for DoD and the services is to prioritize assets at risk from interacting extreme events and related environmental conditions across a wide range of installation types and locations. The task confronting the DoD is enormous. DoD is responsible for 7,000 sites (of which approximately 510 are active installations) and 24.9 million acres of land – it owns and/or operates more facilities than any other federal agency (DoD 2015). Many of the nation's military installations and assets they depend on (energy and transportation infrastructure, etc.) are in areas exposed to frequent extreme weather events, such as naval bases located in hurricane-prone zones. Determining how the configuration of DoD assets will need to change to meet the changing demands of tomorrow—including damages and risks posed by extreme events—requires developing information on potential impacts and their significance to mission continuity and attainment.

Identification of assets at risk must be conducted in an efficient and rigorous fashion and reflect accurate information on at least three issues: (1) how likely different locations are to be exposed to extreme events and related physical conditions (*exposure*); (2) the extent to which these exposures can cause damage and have consequences for important missions (*sensitivity*); and (3) the ability to make changes in infrastructure, management, location, or other strategies to cope with immediate consequences and prevent future damages (*adaptive capacity*). This information needs to be compiled across multiple installations and assets and related to existing planning and decision-making processes in which financial and other program resources are allocated. There are a variety of approaches in the literature for implementing "screening-level" assessments of asset vulnerability/risk (Moss et al., 2016). A statement of need could be focused on developing, evaluating, and applying new/existing methods and tools for use in screening risks to DoD facilities. Successful projects would pair climate scientists, specialists in other physical aspects of exposure (hydrology, fire science, etc.), subject matter experts in related infrastructure systems, and installation/Service/OSD planners and resource managers. These methods could be compiled in a tool kit and made available to the Services and the OSD as they need to respond to Congressional and executive branch requests for reports and plans.

A statement of need could have four components:

- Exposure: In evaluating critical assets it is necessary to determine which exposures are likely to occur at an asset location. Further, any specific asset will only be subject to effects from certain types/classes of hazards (flooding, freezing, extreme heat, drought, etc.), mostly due to vulnerabilities expressed by the asset(s) of interest. This component of the statement of need would encourage innovative approaches for characterizing the likelihood of occurrence of a given type of hazard spatially and temporally. There are numerous challenges to developing approaches that are efficient, consistent across the large number of potentially affected locations, and that reflect variation in likelihood due to specific local conditions (for example topographic conditions that affect likelihood of flooding). Another challenge is to account for changes in frequency, intensity, or duration of extremes over time due to changes in land use and climate. Approaches could include regional or exposure-specific reviews of the state of science, development of threat surfaces or maps of different hazard types, or others.

- Sensitivity/consequences: Different installations and assets will express different levels of vulnerability to the exposures and can be more or less important to mission attainment. This aspect of the statement of need would require development of approaches for evaluation of the consequences both for assets/installations and for broader missions they support. These could include use of extant data relating to the mission importance (e.g., Mission Dependence Index), approaches for evaluating asset condition from real property or other data bases, design of surveys to gather information from installation personnel regarding infrastructure condition and/or historical damages from prior events (such as flooding and heat stress) that could serve as analogs of future conditions, modeling of complex networks of interdependent assets, and others.
- Capacity for coping or adaptation: Another key issue is the ability of installation and mission managers to cope with the consequences of extreme events and other stresses, and to make adaptations to avoid future damages. A screening-level assessment needs to identify factors associated with both challenges and to rank installations or assets on preparedness and adaptive capacity. Effective coping in the immediate aftermath of damages depends on numerous factors including disaster management plans and resources, training, effective leadership, redundant systems that can temporarily provide needed services, and others. In the long term, additional opportunities for reducing or avoid consequences altogether are possible, for example changes in infrastructure design, siting, management, and others. These opportunities require not only the technical alternatives themselves, but also the capacity to implement changes, for example adequacy of budgets, decision rules/standards that permit alterations, flexible building or zoning codes, etc. A major challenge for screening-level assessments is evaluation of coping and adaptive capacity, given the complexity of the concept. Components such as organizational culture, leadership, or informal budgetary flexibility to respond to the unexpected are subjective and difficult to assess and verify.
- Decision context: A final component of this statement of need would be the testing of methods for the above challenges in the context of a specific DoD or Service management system, for example a currently used planning, budgeting, reporting, or decision-making process. These can include installation-level budget processes to Service or OSD-level systems that manage requirements for training or test ranges needed to maintain readiness. Screening information needs to be produced for a specific context, reflecting different time frames/planning horizons. Figure 8-1 identifies example decision/planning contexts and potential users of screening assessments on different time frames: (short, medium, and long-term). All projects responding to the statement of need should be developed and applied with decision contexts in mind, and thus end users need to be involved in project development and implementation.

The recently published Coastal Assessment Regional Scenario Working Group (CARSWG) document (Hall et al., 2016) focuses on the risks of sea-level rise to DoD installations. This screening tool could be used as an example for other hazards to DoD facilities, as well as the basis for understanding whether there are unified screening approaches that could be used across the DoD complex.

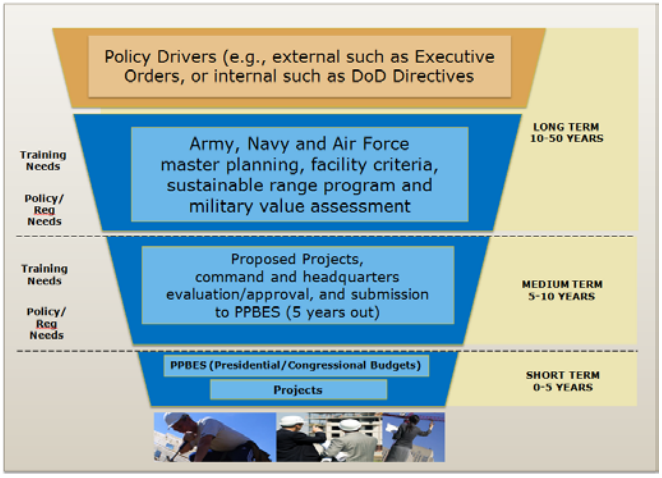

Figure 8-1: Long-, medium-, and short-term elements of planning for DoD infrastructure. Development and evaluation of screening methods needs to take place in specific application contexts such as these.

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9. Notes on research process: integrating "basic" and "applied" research

One of the more interesting aspects of the workshop was the different expectations and "cultures" of participants from the research and practitioner communities. Scientists emphasized the need to continue research until high levels of confidence were attained, while practitioners emphasized that some information, even if incomplete and uncertain, was better than no information. Practitioners reasoned that it was important to provide the current statement of science with appropriate and understandable evaluation of confidence and uncertainty so that this knowledge could be applied to improve ongoing management and decision making.

Another manifestation of this difference was the ways in which the two communities framed research questions and prioritized results. The research community framed questions in terms of their ability to contribute to fundamental or basic research goals. Practitioners indicated the importance of considering their information needs to identify specific phenomena, processes, and variables to be explored in research. Stokes (1997) developed a classification of scientific research that highlights the potential of some projects to both advance fundamental understanding and simultaneously meet societal needs, for example Pasteur's basic research on microbiology which was motivated by the applied need to reduce illness from tainted milk. During the workshop, agreement was reached that properly framed SERDP/ESTCP research need not be "basic" or "applied" and could meet both needs.

The result of these different cultures or approaches is a mismatch between the large amount of Earth systems science information available and the type and format of information needed by engineers, architects and planners at DoD and its services for prioritizing and identifying specific actions required to manage the risks from future uncertain conditions. One reason for this is that model results are not generally produced with the end goal of design in mind. For example, climate impact studies generally focus on mean values of temperature and precipitation, while infrastructure design considerations cover a range of temporal and spatial scales and are primarily concerned with extremes. There are also barriers that are unique to DoD processes. For example, any design under DoD has to be consistent with a set of criteria known as the Unified Facilities Criteria (UFC) to obtain approval, and although UFC has criteria related to weather and climate, the criteria assume stationarity—i.e., that climate patterns will continue as they have in the past. Thus, there is a growing recognition at DoD that the UFC needs to be updated, and information on extreme events made available that could plug directly into the UFC process.

Reflecting these issues, many participants urged taking an "end-to-end" approach for framing and conducting projects that would include (1) fundamental science, (2) application, and (3) evaluation of utility in *each* project. This stands in distinction to more traditional approaches that segregate a basic research project from activities that use new science in applied settings. End-to-end projects would be built around producing information that is "actionable" in planning and design activities. Actionable data and projections can be defined as those that enables practitioners to determine whether a design is likely to be changed or not by using projections compared to historical data alone, or whether the uncertainty may be too large for a given location and/or variable to be useful.

This approach was seen as having multiple potential benefits and could over time lead climate science to be more relevant to risk framing approaches currently in practice, for example fostering

science that focuses on extremes/tail risks and that identifies *most likely* and *maximum probable* occurrences of extreme events at resolutions and time periods of interest to users. Participants felt that an end-to-end approach would require reframing typical SERDP statements of need and could integrate the different programmatic perspectives embodied in SERDP and ESTCP. For example, it would encourage incorporating the perspectives of end users, either by including them in the process of framing and conducting research, or at a minimum through substantial dialogue on issues such as identifying information needs, user defined thresholds, time frames of interest, etc. Participants felt this would be a crucial aspect of fostering improved collaboration between Earth/environmental scientist and practitioners charged with producing practical benefits for DoD in terms of improved performance or economic efficiency.

Reference

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