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Climate Risk Reduction: Hazards and Processes for Operationalizing Climate Information into ASCE Standards and Manuals of Practice

June 24 and 25, 2024

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Foreword

The overarching objective of this partnership between American Society of Civil Engineers (ASCE) and National Oceanic and Atmospheric Administration (NOAA) is to ensure that the Nation's infrastructure is climate ready, i.e., that the design and construction of new and retrofitted infrastructure accounts for, and is resilient against, the increased hazards associated with changes in weather and climate. As of November 1, 2024; the documented 24 disasters with losses exceeding $1 billion have a total cost of $61.6 billion (NCEI, 2024). The full costs of extreme weather and climate events are greater than the insured and documented figure above, which should include lost work, mental stress, and uninsured losses, etc. By helping to ensure that the design and construction of infrastructure is informed by the best available scientific understanding of future weather and climate conditions, this effort should increase the pace of climate adaptation; optimize design, construction, and maintenance costs; and reduce the costs of extreme weather and climate events.

ASCE is identifying its climate and weather data needs to incorporate the best available science into the next generation of civil engineering codes, standards, and manuals of practice (MOPs). In turn, NOAA is identifying how it may be able to respond to these needs with its capabilities over both the near and long term. A formal collaboration between the world's largest civil engineering professional society and the Nation's largest provider of climate information is advancing the use of NOAA-produced climate science and understanding within engineering practice for the design and construction of climate-resilient infrastructure, especially during the development and updating of ASCE standards and MOPs.

This report is part of ongoing activities under a partnership between the ASCE and NOAA. Initial steps towards the partnership were first announced in 2021 with the establishment of a cooperative agreement between the Center for Technology and Systems Management (CTSM) of the University of Maryland (UMD), College Park and NOAA, and a letter of support executed by ASCE to UMD-CTSM for this collaboration. The cooperative agreement led to the establishment of an ASCE-NOAA Task Force for Climate Resilience in Engineering Practice (ASCE-NOAA Task Force). The ASCE-NOAA Task Force, working with the ASCE Subcommittee on Climate Intelligence for Codes and Standards of the ASCE Committee for Adaptation to a Changing Climate (CACC), built on work published as part of the ASCE Manual of Practice 140: Climate Resilient Infrastructure: Adaptive Design and Risk Management (ASCE 2018a) to examine key weather and climate hazards of relevance to engineering practice as manifest in key ASCE standards and MOPs. Upon further discussions, both organizations felt a more formal agreement would be mutually beneficial, so ASCE and NOAA signed a Memorandum of Understanding (MOU) on February 1, 2023 (ASCE and NOAA, 2023a).

In June 2024, the ASCE-NOAA Task Force held a two-day, invitation-only workshop focused on six climate-sensitive hazards of relevance to engineering practice and procedural discussions to accelerate the collaboration of engineering needs and Federal scientific data provision to address the increasing frequency and intensity of extreme weather and climate events. This workshop report is based on material presented in the plenary session and on the outcomes of structured discussions between climate scientists and engineers in breakout sessions during the workshop. Beyond documenting the workshop, the primary purpose of this report is to inform the ASCE-NOAA Task Force when planning its future activities. Additionally, as a public document, those developing climate services for the engineering sector may benefit from this synthesis of the workshop discussions.

Acknowledgements

ASCE provided in-kind contributions consisting of resources, workshop space, and event support, which included audiovisual technology. The ASCE-NOAA Task Force would like to acknowledge the invaluable contributions of ASCE leadership and staff who dedicated their time and expertise, reflecting ASCE's commitment to excellence and collaboration.

The ASCE-NOAA Task Force also acknowledges the significant contributions to this effort by laboratories in NOAA's research arm, in particular the Physical Sciences Laboratory (PSL) and the Geophysical Fluid Dynamics Laboratory, as well as the National Centers for Environmental Information (NCEI), the National Ocean Service, and the National Weather Service. The ASCE-NOAA Task Force acknowledges the commitment and support of NOAA's Climate Program Office. NOAA's financial support included J. Barsugli's time in part by NOAA grant NA24OARX431C0059 and cooperative agreement NA22OAR4320151; D. Walker's and B. Ayyub's time through NOAA COP NA23OAR4310541 and NOAA CPO-MAPP NA24OARX431C0062-T1-01; and notetaking and travel support from Task #1K332P24F0021.

The ASCE-NOAA Task Force populated the workshop participant list to achieve a balance of ASCE and Federal government perspectives. The team acknowledges the commitment of ASCE and NOAA to gender and racial equity. The ASCE-NOAA Task Force expresses its appreciation to all the breakout leads and note takers as well as all attendees who volunteered their time to the workshop (see Appendix A for list).

Disclaimer

Executive Summary

As a nation, the United States makes significant investments in the design, construction, and maintenance of homes, businesses, transportation systems, water resources systems, industrial centers, and other components of the built environment every year. Civil engineering practice, and the guidance documents that shape it, are critical in protecting lives, livelihoods, and property in the face of natural hazards. In recognition of the role civil engineers play in addressing the threat posed by weather and climate disasters to the national infrastructure, the American Society of Civil Engineers (ASCE) and National Oceanic and Atmospheric Administration (NOAA) Task Force on Climate Resilience in Civil Engineering Practice (ASCE-NOAA Task Force) hosted a workshop June 24-25, 2024, at ASCE Headquarters in Reston, Virginia, entitled *Climate Risk Reduction: Hazards and Processes for Operationalizing Climate Information into ASCE Standards and Manuals of Practice*. The workshop addressed both the need for observational and projected weather and climate data related to improving resilience and the challenges of improving the process by which relevant climate data are developed and delivered to the civil engineering community. [Section (Sec.) 1]

Frequency and severity of weather and climate hazards are increasing and projected to increase further. Exposure to those hazards is increasing as well, in terms of population and property at risk, due to new construction and demographic shifts. By addressing natural hazards with updated building codes, it has been estimated that $11 of loss reduction may be achieved per $1 spent, depending on the peril and geographic setting[1]. **To protect people and build a climate ready nation, engineering practices and standards must be revised and enhanced to address climate change and resiliency to ensure they continue to provide low risks of failures and to reduce vulnerability to failure in functionality, durability, and safety over their service lives**. [Sec.6]

Hazards

Based on monthly discussions organized by the ASCE-NOAA Task Force, the workshop included breakout sessions devoted to understanding the civil engineering needs for weather and climate data and data products (e.g., current trends and future projections). Several engineering use cases[2], including the development or updating of standards and manuals of practice produced by ASCE that address six classes of environmental hazard, including:

1. The effects of increasing **temperature and temperature extremes** are already being seen by cold regions engineers. Below-ground structures and infrastructure are critically affected by changing frost penetration of soils and permafrost degradation. With a warming climate, it is also important to anticipate the range of temperatures that exposed building materials may experience over the service life of the structure to improve the

[1] NIBS (2019) found a benefit-cost ratio of 11 to 1 "for adopting the 2018 International Residential Code (IRC) and International Building Code (IBC), the model building codes developed by the International Code Council (also known as the I-Codes), versus codes represented by 1990-era design."

[2] The engineering application or other context where the weather and climate data are used, including the development or updating of standards and manuals of practice produced by ASCE.

performance of the building envelope and limit the degradation of building materials. [Sec. 4.2]

2. **Rainfall extremes** are expected to increase in many regions of the United States as climate warms leading to the potential for increased loads on structures and increased flooding. NOAA Atlas 15, the update to Atlas 14 (Precipitation Frequency Atlas for the United States), will serve a critical data need for structural design standards, stormwater management, and flooding. The need to anticipate future 15-minute rainfall extremes was seen as the most useful, though other duration extremes were also relevant for urban flooding. The need for easier access to input data to support the types of watershed-scale hydraulic and hydrologic modeling was also seen as meeting a wide range of use cases. [Sec. 4.3]

3. **Snow extremes** are projected to change in complex ways depending on location. There is a need for better data and modeling of snow extremes in both the current climate and as a basis for projections of future conditions, particularly in mountainous regions. Access to snow data and projections on daily time scales was seen as a priority to improve treatment of the combined effects of snow, including rain-on-snow events. [Sec. 4.4]

4. **Wind extremes** Tropical Cyclone (i.e., hurricane) wind extremes were seen as having the greatest overall impact on the built environment, while thunderstorm and tornado winds were seen as needing the most additional research. Straight-line winds would also need to be updated based on non-stationarity. Having access to finer-scale climate modeling would help improve the hazard maps for extratropical (synoptic) storm types. There is potential to develop data to support maritime facility design and evaluation [Sec. 4.5]

5. The participants for the **response of earth materials to a changing climate** breakout identified necessary enhancements to characterization of future groundwater changes, in particular changes in the elevation of the water table as a key data need. Coastal region groundwater levels are being affected by sea-level rise and thus have different data needs than inland regions. The changing nature of landslide hazard, such as mass movement of rock and soil, is a critical engineering hazard that is related to both long- and short-term rainfall extremes, land cover change, and erosion. [Sec. 4.6]

6. The data needs for **compound flooding** are complex and depend on the particular combination of flooding processes that are dominant for a given application. For coastal regions, the combined effects of sea-level rise, tides, storm surge, and waves were noted, particularly between the locations of tide gauges. NOAA's Coastal Reanalysis (CORA) dataset includes historical values of water level and waves that can serve as a basis on which to model projections. For urban flooding, in addition to short-duration rainfall extremes, data and information needs include river levels, between gauges, groundwater levels, and other factors. A compound flooding manual of practice is under development. [Sec. 4.7]

In addition, **cross-cutting priority data needs** emerged that would serve many engineering use cases: Completion of NOAA Atlas 15 for short duration rainfall extremes, projections of Air

Freezing Index and other temperature indicators used by cold regions engineers; provision of input variables for use in watershed-scale hydraulic modeling of flooding; development of projections of changes in groundwater; and the continued development of data products to support compound flooding, including NOAA's Coastal Reanalysis. [Sec. 4.8].

A Repeatable and Recurring Process for Updating Climate Information

Discussion held during the monthly meetings of the ASCE-NOAA Task Force identified and affirmed the needs of a clear and sustained delivery of key data, information, and other related products. This will require ongoing engagement among the members of various ASCE bodies responsible for the development and updating of appropriate guidance, including the authoring committees of ASCE standards and Manual of Practice (MOPs). **The key process challenges addressed during the workshop focused on the alignment of climate science development, Federal funding cycles, and timelines of updating engineering standards.**

The long and highly regulated development cycle of standards was seen both as a necessity and a challenge. Given the yearly investment in the built environment, many construction projects cannot wait until updated standards are adopted. Four areas were identified as priorities to improve climate resilience in the near-term: **Identifying interim products** and mechanisms to inform civil engineers while the standards are being updated; **education and outreach to engineers** about new datasets and methods to address non-stationarity; **implementation planning**; and **developing the Return on investment (ROI)** on addressing climate change for specific engineering applications. [Sec. 5].

Federal agencies rely on a number of mechanisms to fund the research needed to advance building codes and standards, but with the exception of seismic hazards, long-term funding is rare. The National Earthquake Hazards Reduction Program (NEHRP) model was held up as a successful example of the improved coordination of research and standards timelines and the consistent improvement from cycle to cycle that can be achieved with long-term funding. The clear message emerged that **continued, long-term funding for climate risk reduction, as in the NEHRP model, would reap many benefits of coordination and effectiveness. [Sec 3.2]**

Using Global Warming Level (GWL) to describe future climatic conditions has been proposed for ASCE 7-28. The GWL approach has many advantages that may aid in the delivery and uptake of climate services for engineering. [Sec. 3.3]

There is a critical need for Federal agencies to provide the foundational and applied research to support climate risk reduction and to co-develop and deliver authoritative climate projection data for use by the engineering sector. To be effective, the following principles of engagement were identified as important: Transparency and co-development of products, greater specificity and reliability of the data products, ability to anticipate needs, wider integration of Federal efforts, and more focus on dissemination and use. [Sec. 6] As one such effort that is centered on co-development, NOAA is standing up the Industry Proving Ground (IPG), a project to improve delivery of climate data and services for the architecture and engineering; finance and reinsurance; and retail sectors. The IPG is engaging with ASCE as an early partner. [Sec. 3.1]

In summary, discussions over the two-day workshop suggest the ASCE-NOAA Taskforce should pursue the following activities in the coming year [Sec. 6]:

- Continue to encourage focused discussion and co-development of climate information needed for efficient design and operation.
- Promote cross-engineering discipline dialogue and bring that integrated perspective to discussions with its Federal participants, especially NOAA, as they examine ways to support ASCE's use of climate information in its standards, MOPs, and other products.
- Extend the value of the ASCE-NOAA Task Force efforts, building on past efforts, to forge new connections through coordinated engagement among relevant NOAA and other Federal programs and ASCE institutes, technical groups, and committees.
- Facilitate a broader discussion of how data and data products can be presented in an integrated and user-friendly environment to meet the needs of ASCE members and various committees, whether drawing from existing Federal data portals and web services or developing new datasets, portals, and services.
- Develop an overarching process to set priorities and disseminate data and products.

1. Introduction

The June 2024 American Society of Civil Engineers (ASCE) and National Oceanic and Atmospheric Administration (NOAA) workshop began with a brief history of the project and key insight from the budget and standards process. The coordination among the Federal budgetary process, standards process, and research timeline emerged as a theme from the workshop (see textbox).

Brief ASCE-NOAA Partnership History

ASCE-NOAA Task Force for Climate Resilience in Engineering Practice (ASCE-NOAA Task Force) was established in 2021 to facilitate the collaboration between the ASCE and NOAA. ASCE and NOAA signed a Memorandum of Understanding (MOU) on February 1, 2023 (ASCE and NOAA, 2023a). The major objectives of the partnership stated in the MOU are as follows:

- Improve cooperation in development and delivering climate information and services required by civil engineers and allied professionals in order for them to design, build, operate, and maintain climate-resilient infrastructure.
- Facilitate ASCE's efforts to update its published and educational content to reflect the best available climate information.

1.1. Background and Motivation

As a nation, the United States makes significant investments in the design, construction, and maintenance of homes, businesses, transportation systems, water resources system, industrial centers, and other components of the built environment every year. The Value of Construction Put in Place for 2023 is estimated by the Census Bureau (2023) to exceed \$2 trillion, including over \$1.5 trillion of private investment. In addition, these efforts are a source of millions of American jobs. According to statistics provided by the Bureau of Labor Statistics over 8 million (seasonally adjusted) employees were involved in U.S. construction as of October of 2024 (Bureau of Labor Statistics, 2024).

While awareness of the importance of climate resilience is growing among the professional communities of practice involved in the siting, design, financing, and construction of the built environment, significant challenges to systematic and well-informed action remain. Chief among these is the well-documented gap between current understanding of the evolution of the probability of relevant weather and climate extremes and engineering practice. While this "gap" takes many forms, one of the most illustrative is the lack of systematic treatment of climate change in most building codes and standards in the United States and abroad. Recent work by the International Codes Council concluded that, globally, "Climate data is frequently only updated on a 10-year cycle on average, so as weather becomes more severe from year to year, the underlying data simply does not accurately reflect the risk to the building of these extreme weather-related events" (IPCC, 2021). This non-stationarity is easily observed in the evolution of 30-year climate normals produced by NOAA (NCEI, No Date). Thus, while standards updated on a regular basis can account for changes in the observed record through time, they still fail to account for the inherent bias that is introduced by relying on data from periods where the fundamental driver of climate change, the concentration of atmospheric greenhouse gases, is different than that expected during the design life of a building, culvert, bridge, or roadway. This problem is especially acute for design periods that may extend beyond 2050 when accumulation of greenhouse gases (GHGs) will likely result in accelerated changes in the probability of exceedance for many key design factors such as storm severity (Walker and Ayyub, 2022).

The lack of appropriate incorporation of information about future weather and climate in the various standards and associated building codes is a significant challenge, even for the well-informed civil engineer. The community of civil and environmental engineering practice is expected to provide clients with cost effective options for achieving acceptable levels of risk. Documenting and characterizing the risk of failure under a variety of scenarios, especially for complex engineered systems that are sensitive to a variety of weather and climate phenomena, requires significant intellectual resources that can drive up project costs and strain project timelines. Although the civil engineering community is generally well-versed in the management of uncertainty, the complexities and limitations of projections of future weather and climate conditions, at temporal and spatial scales of relevance to specific engineering problems, remain a significant barrier to systematic improvement in infrastructure resiliency.

Information developed by climate scientists to inform high-level policy decisions or broad planning efforts is often of limited value in selection of sites or design parameters at the project scale. Conversely, climate research intended to provide actionable information to inform engineering decisions is limited was often developed to serve generic needs without a thorough understanding of specific problems the end-user community may be facing or the tools at its disposal. Closing the gap between what is available and what is needed also requires a much closer examination and treatment of a variety of sources of climatic uncertainty and how these may be incorporated into engineering design and practice.

ASCE recognizes that the design life and purpose of physical infrastructure plays a role in determining its sensitivity to changes in weather and climate extremes (ASCE, 2018, ASCE, 2021a, and ASCE, 2021b). As a result, determining the value of various types of information (e.g., modeling/predictive versus observational), as well as quantification and communication of uncertainty, will likely need to be framed with respect to specific design standards or engineering use cases. Both climate scientists and engineers can thus benefit from a collective understanding of end-user problems developed through fostered interaction between the two communities of practice.

Naming of ASCE Standards/MOPs

This report refers to ASCE standards and manuals of practice by their number and when relevant, the year of publication. Hence, ASCE 7 refers to Minimum Design Loads for Buildings and Other Structures, and ASCE 7-22 to the 2022 published standard. A future year, as in ASCE 7-28, refers to a planned update to be published in 2028. Full reference to the standard name, including reference to ASCE institutes and the full title are in Appendix E.

1.1.1. 2022 Workshops and the ASCE-NOAA 2023 Report

In fall 2022 the ASCE-NOAA Task Force held a series of workshops intended to bring together subject matter experts on a variety of weather and climate trends and processes, as well as authors of key ASCE standards and manuals of practice (MOPs) to evaluate methods for understanding environmental conditions relevant for engineering design. The resulting workshop summary report, *Leveraging Earth System and Modeling to Inform Civil Engineering Design*, reflects efforts to prioritize hazards relevant to the imminent deadlines for the ongoing update of ASCE 7-28. The workshops focused on the civil engineering implications of four weather and climate related hazards: temperature extremes, intense rainfall, straight line wind, and coastal flooding. *Leveraging Earth System and Modeling to Inform Civil Engineering Design* captures the outcomes of structured discussions between climate scientists and engineers on these hazards and the associated engineering uses. One topic of particular concern was the production schedule of NOAA's Atlas 15, which will be the update to the heavily used Atlas 14 of precipitation frequency that is referenced in multiple ASCE standards (ASCE and NOAA, 2023b).

The activities of the ASCE-NOAA Task Force (Figure 1.1) serve to strengthen the connection between climate scientists and various ASCE entities and activities. For example, several climate scientists now serve on or have been consulted by the future conditions' subcommittee of the ASCE 7-28.

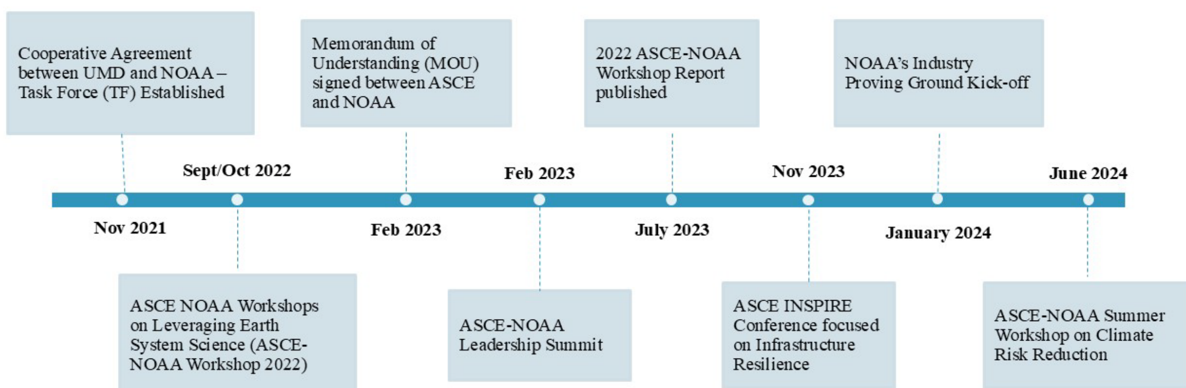

Figure 1.1 Timeline of Selected ASCE-NOAA Task Force Activities. Major activities of the ASCE-NOAA partnership to integrate the best available weather and climate information into civil engineering standards from November 2021 to June 2024

1.2. 2024 Workshop Climate Hazards for ASCE Standards and Building Practices

Based on discussions taking place across multiple ASCE-NOAA Task Force meetings and at the ASCE INSPIRE Conference held in November of 2023, and to fulfill their joint commitment to meet annually, ASCE and NOAA agreed to hold the first in what is anticipated to be a series of summer workshops on weather and climate resilience in civil engineering practice. *Climate Risk Reduction: Hazards and Processes* was held at ASCE headquarters in Reston, Virginia, on June 25-26, 2024. Participants of this hybrid workshop included individuals from several ASCE institutes and technical committees, spanning multiple civil engineering communities of practice, as well as key experts from NOAA and other Federal agencies responsible for providing weather and climate information. The workshop focused on technical and procedural needs to operationalize the integration of the best available weather and climate information into ASCE standards and MOPs as a key approach to increasing infrastructure resilience in a changing climate.

In comparison to the 2022 workshops, the 2024 workshop broadened the scope of engineering practice to include a wider array of engineering guidance, including ASCE MOPs, and to explore other engineering use cases. The 2024 workshop also focused on needs beyond the immediate round of ASCE updates to allow the ASCE-NOAA Task Force to assess scientific gaps and explore options for streamlined processes for integration into future ASCE updates.

The Task Force identified six classes of climate- and weather-related hazards for inclusion in the workshop program: extreme temperature (with an emphasis on cold regions), intense rainfall (needs beyond ASCE 7-28 including stormwater and flood design), changes in the occurrence of frozen precipitation (emphasis on snow), intense wind including tornados, changes in earth material behavior related to temperature precipitation and hydrologic change, and compound flooding (due to the combined effects of more than one flood mechanism). Selection was based on a review of numerous existing ASCE standards and MOPs as well as written and verbal input from four major ASCE institutes that produce the majority of ASCE standards and MOPs. Workshop attendees explored these hazards and their implications for engineering practice through a series of technical breakouts discussed in Section 4.

Roughly half the presentations and breakout sessions focused on the need to develop a sustained process for connecting climate information to engineering practice. The procedural breakouts highlighted challenges due to lack of consistent funding to support the research and translation of scientific findings needed to inform engineering practice. ASCE standards committees have engineering and other professional backgrounds members that are volunteers; the committees have limited capacity to perform research. Conducting climate research or implementing significant changes to climate and weather data sets require resources and long lead times. Thus, ASCE and NOAA recognize the benefit for incorporating civil engineering data needs early in the climate research and product development process.

1.3. Understanding the Cycles of Engineering Standards Development and Climate Science Funding

The summary that follows reflects the contributions, expertise, and viewpoints of the speakers during plenary sessions of the workshop and ensuing discussions by workshop participants. Recordings of the presentations are linked in Appendix B and provide more detail and original context for statements summarized here.

The characterization of future conditions for use in engineering design for infrastructure projects with design lives of 30-100 years or more must account for anthropogenic climate change. The workflow to develop suitable climate projections to meet this need is complex and beyond the control of any one end user group. The dominant approach relies on global climate models (GCMs) that account for projected changes in global atmospheric composition due to the release of GHGs and other anthropogenic factors. The development of useful products at the local scale requires considerable analysis and post-processing of the GCM output, including such steps as downscaling, bias adjustment, and climate impacts modeling though such tools as hydrologic models or empirical hurricane models. In addition, there is the effort needed to update the analyses of historical observations to take into account recent trends. An example of this is the development of NOAA Atlas 15 Volume 1 that will provide a non-stationary extreme value analysis of precipitation frequency in the historical period to replace Atlas 14.

The development and updating of ASCE standards and MOPs have their own timelines and may be out of sync with the typical development cycles of climate projections. The process developed to provide support for civil engineering practice must therefore be flexible enough to account for complexities and asynchronous actions by entities responsible for various component steps in the overall workflow. Federal agencies play a crucial role in the updating of historical analyses, the development and running of GCMs, and the development of products suitable for engineering applications. Federal agencies also are a substantial financial sponsor of infrastructure new construction and upgrades through direct funding or block grants. In order to enhance mutual understanding of these processes, a workshop plenary session reviewed the contrasting timelines of standards development and the Federal budgetary process.

1.3.1. Understanding ASCE Standards and Building Code Cycles for Climate Risk Reduction

A standard is a document that describes the processes and methods that must be performed in order to achieve a specific technical or management objective. ASCE standards define minimum criteria for performance, such as building performance in response to environmental hazards. Compliance with hazard-based standards improves community resilience because infrastructure and buildings that are designed and constructed to minimum standards are more likely to withstand extreme events at or below the hazard design level. The relationship between ASCE standards and infrastructure resilience is:

- Standards define how to design and construct a variety of buildings/infrastructure by relying on research and data.
- National and local building codes define if, when, and in what manner construction is permitted, and which civil engineering standards are referenced.
- Local jurisdictions adopt and enforce codes to protect health, safety, and welfare of the public (Goupil, 2024).

Underlying research and data specifically developed for adoption into building codes and standards is critical. With some exceptions (noted in section 3), federally funded climate data and data services have not been developed with this specific end use in mind, particularly in regard to climate projections. As a result, standards developers have experienced barriers and challenges when attempting to use this information efficiently or effectively. The research and data development timelines are lengthy, and often undefined, which complicates coordination for ingesting and incorporating the information. Adding further challenge to gathering data for development or updating of a civil engineering standard is the fact that funding cycles for research and data development can vary over time and may tailored for other applications.

The lengthy time periods for civil engineering standard development and code adoption are well-defined and heavily structured, creating limited windows for accepting data. The timing for establishing the foundational data for civil engineering standards can be misaligned with the source data development. Time from initial research/data development to adoptions by jurisdictions can easily take 10 years (see below figure).

Code Development Process

The International Code Council development process for the I-Codes, including the International Building Code (IBC) requires compliance with an accepted consensus process such as those developed by the American National Standards Institute (ANSI). ANSI mandates the ability of people affected to participate, documentation of a consensus vote, and requires participants of diverse interests, specifically "all who are directly and materially affected by a standard under development, including consumers and the general public" (ANSI, 2024a and ANSI, 2024b).

Figure 1.2.1 How Research Informs Building Codes. Research supports ASCE development and updating of standards, which are adopted as International Building Code (IBC), and then adopted, whole or in part, by local jurisdictions (Goupil, 2024).

Federally funded programs and agency funded research (through Federal Emergency Management Agency (FEMA), National Institute of Standards and Technology (NIST), NOAA, and others) develop the environmental hazard data relied upon for national standards development. ASCE has found consistently funded and well defined and developed programs, such as National Earthquake Hazards Reduction Program (NEHRP), provide efficient and impactful results.

1.3.2. Federal Budget and Program Cycles Orientation

Having a consistently funded, direct pipeline for climate-informed environmental hazard research and data development for use in design standards and building codes would accelerate and sustain incorporation of data needed for hazard-based standards (such as in the NEHRP example above). The presentation summarized the process and timelines through which programs are funded by the Federal government. Several key concepts were discussed including authorization, appropriation, and supplementals along with the time horizons involved.

A fundamental issue clarified was the difference between authorization and appropriation. Authorization legislation provides the legal ability to spend federal money but does not commit any funds. Appropriation allocates funds for a given fiscal year (FY). Some appropriations are mandatory for each year while others called discretionary are dependent on securing funding each year. Consequently, programs may be legally allowed (authorized) without any money to execute the work (no appropriated funds; see figure below for more details between authorization and appropriation). A supplemental appropriation is an appropriation enacted outside of the regular annual appropriations when the need for funds is too urgent to be postponed. These supplemental appropriations are one-time infusions of money.

The federal FY runs from the beginning of October to the end of September. For example, FY25 is October 1, 2024, to September 30, 2025. The budget process within a Federal agency starts years before the work is executed. Dozens of specialized committees in both the House of Representatives and Senate follow a lengthy process of planning and executing within the agencies for budget requests.

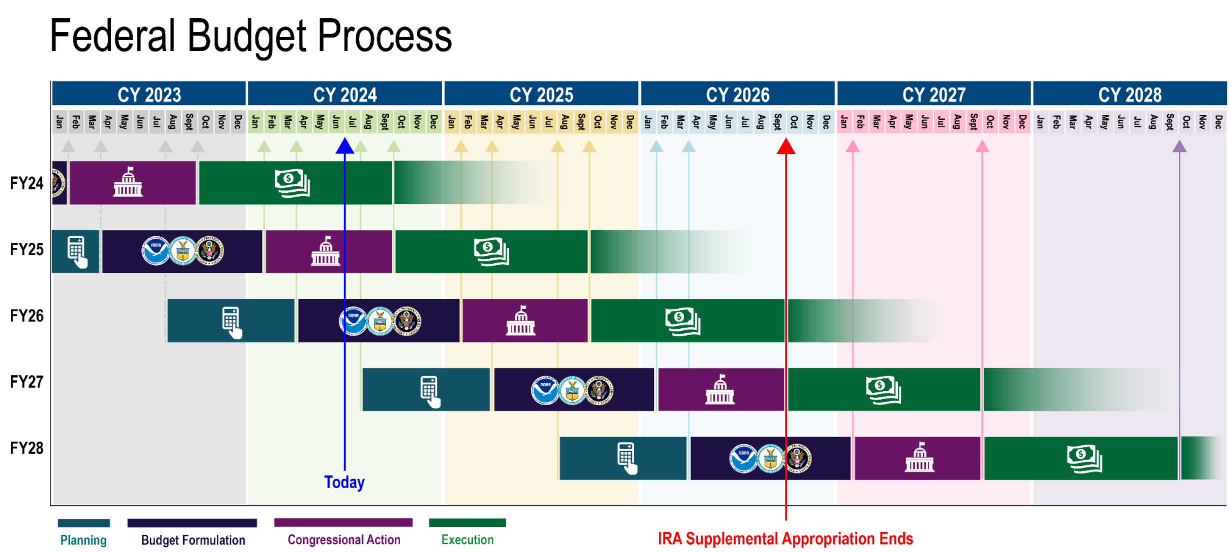

Figure 1.2.2 Federal Budget Appropriations Timeline. Planning begins at least two years before the program is executed (Sevier and Pica, 2024).

Understanding how asynchronous and inconsistent funding may impact projected timelines for data and data product development is a key challenge of efforts to incorporate that information into engineering guidance developed by ASCE and other standard setting bodies.

2. Needs and Priorities by ASCE Institutes

The summary that follows reflects the contributions, expertise, and viewpoints of the speakers during plenary sessions of the workshop and ensuing discussions by workshop participants. Recordings of the presentations are linked in Appendix B and provide more detail and original context for statements summarized here.

Presidents and past-Presidents of four ASCE institutes presented their perspectives on needs for addressing climate-sensitive hazards. Overall, the session highlighted the importance of using a consistent reference point for climate projections in standards while recognizing the need for ongoing research and collaboration to address emerging challenges and refine methodologies (see textbox).

Key Points in Section 2:

ASCE institutes identified aspects of their engineering practice that are sensitive to a changing climate. ASCE's various institutes rely in different measures on standards, MOPs, and other guidance documents. Key points included:

- SEI relies heavily on standards.
- EWRI and COPRI emphasize MOPs more heavily.
- G-I collaborates on standards and develops "standards of practice" for their engineers.

2.1. Environmental & Water Resources Institute

The Environmental and Water Resources Institute (EWRI) primarily relies on MOPs but also produces standards. The EWRI presentation covered the organization's climate data needs and the feedback received from surveying their members. EWRI focuses on water-related infrastructure and relies on various climate data for engineering work, such as water balance calculations, water infrastructure sizing, and water quality management. EWRI water resources engineers indicated a strong need for reliable data to support their ability to work effectively.

EWRI has surveyed their members on their use of NOAA data (Figure 2.1). Key data sources currently used include NOAA Atlas 14 (Precipitation Frequency Atlas of the United States), historical rainfall station data, probable maximum precipitation (PMP), and temperature data. They require high-resolution rainfall data, ideally on a 5- to 15-minute basis, to support stormwater infrastructure design and other designs where systems response times are rapid.

EWRI members are eager for NOAA Atlas 15 and would like it to include monthly maxima (not just annual maxima) and shorter return intervals (lower annual exceedance probabilities). They requested continued review and transparency of NOAA's methodologies. Additionally, there is interest in expanding climate data to include wind, humidity, cloud cover, solar radiation, stream flows, and river bathymetry to improve energy systems modeling and water supply management.

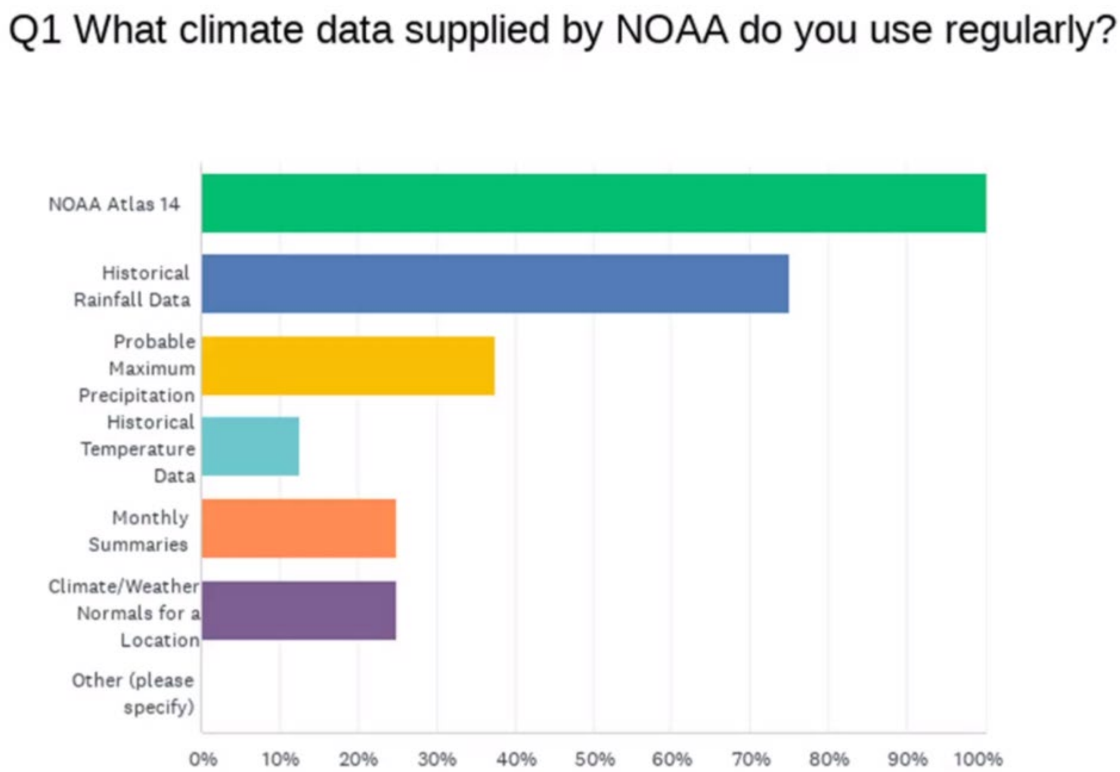

Figure 2.1 EWRI Survey of Its Members' Use of NOAA Data. NOAA Atlas 14 is used by all EWRI survey respondents with the next most used source being historical rainfall data (Clark, S., Scott, D., Mattei, N. J., and Nikolaou, S., 2024).

2.2. Structural Engineering Institute

The Structural Engineering Institute (SEI) presentation reviewed how SEI utilizes climate projection data in standards development, in particular the future conditions chapter of ASCE 7-28. SEI is interested in moving from environmental hazards being historically defined to developing criteria based on projected or modeled data. ASCE 7 is a key reference in other ASCE standards. The ASCE 7-28 future conditions chapter is under development and is gathering the best available data from multiple sources.

In SEI's experience, NOAA provides broad scale climate predictions, and these are refined to regional scales in collaboration or coordination with NOAA. SEI committees then convert regional data into specifications for environmental hazards such as straight-line wind, tornadoes, snow, and floods. The basis for the future conditions chapter is a three degree Celsius (3°C) increase in global mean temperature from pre-industrial levels by the year 2080- 2100. In particular, SEI has needs for projections of climate and weather extremes that are used in the load calculations of ASCE 7. The deadline for inclusion of data into the ASCE 7-28 update is early 2025, and most of the work on that was already in motion by the date of the workshop.

Looking forward to future standard updates such as ASCE 7-34, SEI expressed the need for high-resolution gridded projection data (25 kilometer or less) for accurate hazard predictions, covering all US and emphasizing the need for this data to cover US territories as well. SEI's standards and MOPs, including 14 out of 25 standards and 4 out of 8 MOPs, will eventually incorporate climate data (both observed and projected values) produced by NOAA. More information on the use of environmental hazard data in ASCE 7 can be found in the summary of the panel discussion in Section 3.2 and in the hazard breakout summaries in Section 4.

2.3. Coasts, Oceans, Ports, and Rivers Institute

The Coasts, Oceans, Ports, and Rivers Institute (COPRI) presentation addressed the impact of climate change on infrastructure managed by COPRI members. The presentation highlighted an increase in disaster spending and emphasized the need for resilient infrastructure to mitigate the effects of climate change. However, Federal supplemental spending on infrastructure often rebuilds to prior conditions or "putting back what was there" whereas resilience for future conditions is desired.

COPRI focuses on MOPs more than standards. The COPRI engineers also rely on committee reports. Table 2.3 contains ongoing and *upcoming standards* related to waterfront structures, including dry docks, piers, and wharves. These standards address various climate change impacts, such as sea level rise, wind loads, and effect on corrosion. COPRI's work involves developing practice standards and manuals that will need to account for factors such as sea level rise, storm surge, and compound flooding, and including both the direct and indirect effects of climate change. The presentation underscored the importance of updating design criteria based on current and accurate climate data, which includes addressing gaps in data and refining standards to meet evolving needs.

Table 2.3 COPRI's Ongoing and Upcoming Standards and MOPs

Title	Number	Anticipated Date of Completion	Climate Change Impact
Additional MOP to complement 130 Protection and Rehabilitation of Waterfront Structures	MOP (#To Be Determined (TBD))	Goal is June 2025	Yes
Waterfront Facilities Inspection	MOP 130 2e	Likely 2026	Yes
Design of Low-cresting Marsh Sills	MOP (#TBD)	Goal 2026	Yes
Underwater Investigation	MOP 101	December 2023, somewhat superseded by MOP 130	Yes
Sea Level Change: Considerations for Port Infrastructure		Goal of May/June 2025	Yes
Seismic Design of Piers and Wharves	STD 61-14	Late 2025/ early 2026	No
Dry Dock Standard (based on MOP 221)	STD 77-22	Unknown	Yes
Design: Piers and Wharves, Mooring and Berthing	N/A	2026/2027	Yes

Source: (Clark, S., Scott, D., Mattei, N. J., and Nikolaou, S., 2024).

2.4. Geo-Institute

The Geo-Institute (G-I) presentation provided an overview of the institute's efforts and needs related to climate change. The G-I members develop guidelines and standards for geotechnical practice through their Professional Practice Committee. The G-I is working through the activities below to integrate climate considerations into geotechnical practice and improve standards and guidelines to manage associated risks (Figure 2.4).

The G-I participates in updating codes and standards with organizations such as ASCE and ASTM (formerly American Society for Testing and Materials). G-I members develop guidelines and standards for geotechnical practices and collaborate on projects such as the Data Interchange for Geotechnical and Geoenvironmental Specialists (DIGGS), which standardizes the sharing of geotechnical data.

The G-I addresses how climate change affects geotechnical risks, including soil stability, sea level rise, land subsidence, and extreme weather events. They note increased risks from factors such as soil saturation, liquefaction potential, and erosion. Recent earthquakes around the world have demonstrated the impact of climate-induced changes in the capacity of the soil and foundations to withstand the seismic forces.

As with other institutes, G-I is involved in various initiatives such as publishing research, collaborating with other professional organizations, and exploring innovative solutions. The G-I has established a board-level committee on innovation with a focus on promoting advanced technologies that can improve resilience, risk-informed decision-making, and applications of new tools like artificial intelligence and remote sensing.

G-I emphasizes the need for better data collection and methodologies to address short-term and long-term impacts of climate change on geotechnical engineering. They aim to enhance understanding and decision-making related to infrastructure resilience and recovery.

Figure 2.4 Geo-Institute Climate Sensitive Hazards. Listing of multiple geotechnical risks that are increasing with non-stationarity (Clark, S., Scott, D., Mattei, N. J., and Nikolaou, S., 2024).

2.5. Panel Discussion

The panel discussion included conversation around the rationale for SEI's choice of the 3°C warming scenario and why a particular value was chosen instead of using a range of scenarios. The 3°C scenario was chosen based on a climate impacts workshop held by SEI where it was deemed a median value that was not extreme but more representative of projected conditions. The deterministic value of 3°C was selected for consistency and practicality across various hazards rather than a probabilistic treatment. It was emphasized that the standards specify minimum requirements. The details of how different climate models affect environmental factors are complex and may be investigated further in specialized settings.

Other clarifications and suggestions included the use of grid size and consolidation of data needs across the ASCE standards. Smaller grid resolutions were desirable but computationally intensive and not necessarily more accurate, making them less feasible for current practices. Finer resolutions are utilized when available. Improving collaboration on climate data needs and tool development between different ASCE institutes, like SEI and COPRI, would avoid duplication and align efforts. Integrated approaches across hazards even within a single standard such as ASCE 7 will be important as well.

Future areas of research and needs were voiced. This discussion centered on data needs that may not be met by a single product. Examples included design for permafrost and coastal environments, rain on snow hazard, and the calculation of combined loads from multiple hazards. Finally, emerging research on cascading hazards was mentioned as a potential source of complex data needs.

3. Climate Services Delivery for Engineering

The summary that follows reflects the contributions, expertise, and viewpoints of the speakers during plenary sessions of the workshop and ensuing discussions by workshop participants. Recordings of the presentations are linked in Appendix B and provide more detail and original context for statements summarized here.

Federal agencies rely on a number of mechanisms to fund the research needed to advance building codes and standards, but with the exception of seismic hazards, long-term funding is rare. NOAA is standing up the Industry Proving Ground (IPG) that was funded by the Inflation Reduction Act (IRA) to improve delivery of climate services for the architecture and engineering; finance and reinsurance; and retail sectors. The IPG will engage with ASCE as a critical early partner (see textbox).

Key Points in Section 3:

Each Federal agency panelist described their agency's role in providing environmental data for engineering practice with focus on a hazard for the ASCE 7 (see the summary in each subsection for more information).

- The National Earthquake Hazards Reduction Program (NEHRP) was seen as an effective model. NEHRP provides long-term continued funding to develop and update seismic hazard maps, allowing for greater coordination of the research with standards timelines.
- Four federal agencies work in close coordination to improve the Nation's understanding of earthquake hazards and to mitigate their effects through NEHRP: NIST, FEMA, United States Geological Survey (USGS), and National Science Foundation.
- Using Global Warming Level (GWL) to describe future climatic conditions has been proposed for ASCE 7-28. The GWL approach has many advantages that may aid in the delivery and uptake of climate services for engineering.

3.1. NOAA NCEI Industry Proving Ground Opportunity for Co-Development of Climate Science Data for Engineering

Civil engineering practice plays a key role in developing climate resilient infrastructure. On January 23, 2024, the Department of Commerce (DOC) and NOAA announced an $85 million investment in the new IPG program to promote the development and use of actionable climate information. This initiative, which is funded through the Inflation Reduction Act , will be led by NOAA's National Centers for Environmental Information (NCEI).

The IPG has four components, the largest of which focuses on improving the delivery of NOAA climate data and services to American industries. Additional components are engaging in technology partnerships with small businesses, risk modeling to support decisions, and evaluating the use of NOAA deliverables and to improve the effectiveness of climate adaptation strategies. These components are anticipated to have several major outcomes, the primary being the development of datasets, products, and services that are designed to inform decision making and resilience. Other anticipated outcomes include improving the sector's literacy of NOAA information and ensuring other sectors benefit from the program's investments. Several overarching principles guide the program, such as improving the usability of public-facing NOAA information and delivering quick and impactful wins early with durable wins throughout.

ASCE is considered a critical partner from the architecture and engineering sector because specific requirements can be harvested across ASCE institutes representing a broad spectrum of practice and because over 40 ASCE standards have been identified as sensitive to climate. In addition, NOAA and ASCE already have an MOU focused on climate resilience, with the ASCE-NOAA Task Force helping the Nation account for climate in future infrastructure design and construction, and a track record of holding joint workshops and engagement activities. These activities have already led to documented data and infrastructure requests that can support the sector, such as an industry-focused web portal, as well as specific development opportunities, ranging from a typical meteorological year product to an update of engineering weather data. As IPG proceeds, it is expected that additional engagement activities will refine requirements into new product lines that will be co-developed in close collaboration with ASCE and the sector at large.

3.2. Panel: Programmatic Approaches for Durable Federal Agency and ASCE Coordination to Support Engineering Guidance Development

ASCE has a well-defined process for the adoption of standards. The ASCE 7 update process is one of the most regulated within ASCE, with a regular and reliable update schedule and hard deadlines to feed into the IBC updates. A process that works for ASCE 7 will likely work across other standards. Opportunities for faster adoption include direct adoption of standards when published (skipping the IBC process, for example. See Section 1.3.1.) and inclusion into MOPs that can be used by design engineers or adopted by local jurisdictions.

The ASCE Hazard Tool is available at: https://www.ascehazardtool.org. It is the primary platform for access to hazard data for ASCE 7 and for ASCE 41 (seismic retrofits) with more expansion planned. The web-based tool pulls data from Federal partner web services. It is completely free for all to use with the intention that builders and Federal regulators could readily access the data.

This panel presentation focused on the process by which research and development from Federal agency partners is adopted into ASCE 7 (Figure 3.2). These collaborative and co-development efforts developed organically and differ across the hazards considered in ASCE 7. Funding mechanisms and challenges, timelines, stakeholder engagement, data delivery, and other aspects of the process are discussed here as potential examples going forward on other standards and MOPs. A short summary is provided at the beginning of each agency section in italics followed by more detailed information.

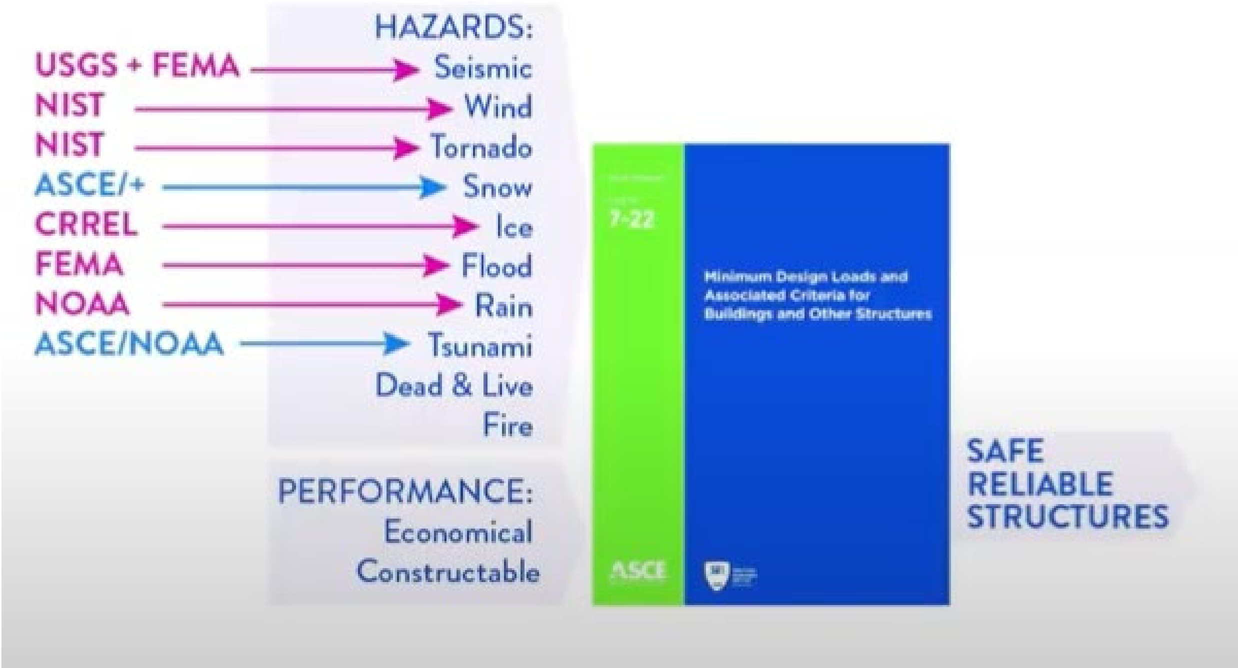

Figure 3.2 Federal Agency Partners for Various Hazards Addressed in ASCE 7. NEHRP has Federal appropriations to produce seismic data for regular updates to the standard. None of the other hazards have consistent funding as they are funded by discretionary appropriations for Federal researchers or for other researchers through grants and contracts; in-kind work and volunteer service may also occur for standard development. ASCE also has funded development for some hazards including snow loads and tsunami hazard mapping (Goupil, 2024).

3.2.1. United States Geological Survey and NEHRP: Seismic Hazard

The United States Geological Survey (USGS) develops and updates the National Seismic Hazard Model (NSHM) on a four to six year cycle that is the basis for seismic risk maps. The process is consistently funded through NEHRP appropriations. USGS collaborates closely with NEHRP and ASCE 7 committees through membership and liaisons, and engineers employed by USGS engage directly in outreach to ASCE and other stakeholders.

USGS products are critical in the development of civil engineering building codes and standards. Partnering with the public is an overarching aim of the organization, such as the ongoing work with ASCE. The USGS Earthquake Hazards Program (EHP) includes the NSHM project that produces maps of the probability of exceedance for the intensity of ground motion (USGS, 2022). The Design Ground Motions task within the NSHM includes up to three USGS engineers who directly interact with users (such as ASCE members) to transform NSHM data into usable downloads for practicing engineers (USGS, No Date).

The NSHM is updated on a four to six year cycle. USGS-developed data is rarely ready for immediate sharing with engineers. USGS engineers serve as liaisons on the National Institute of

Building Sciences Building Seismic Safety Council (BSSC) Provisions Update Committee (PUC) committees to facilitate coordination and the transfer of data.[3]

NEHRP provisions are updated approximately every six years in tandem with ASCE 7 cycles. NEHRP adopts USGS NSHM (hazard model) maps following their own procedures, which are subsequently adopted by ASCE 7. This process takes a few years. Over the course of an additional year, ASCE 7 standards are proposed to, and adopted into, IBC as shown in Figure 3.2.1.

USGS NSHM	NEHRP Provisions	ASCE 7 Standards	IBC
1996	1997, 2000	1998, 2002	2000, 2003
2002	2003	2005	2006, 2009
2008	**2009**	**2010**	2012, 2015
2014	2015	2016	2018, 2021
2018	**2020**	**2022**	2024, 2027
2023	2026	2028	2030

Figure 3.2.1 Recent Iterations of National Seismic Hazard Model Through IBC Adoption. USGS's model is adopted into NEHRP provisions (published by the Building Seismic Safety Council), which are then adopted into the ASCE 7 standard. Consistent funding of NEHRP has ensured that this process has been iterated successfully for over 25 years (Goupil, J., Rezaeian, S., McAllister, T., Ingargiola, J., and Wei, Y., 2024).

As an example of the timeline, the latest USGS NSHM was published in 2023, a NEHRP provision is forthcoming in 2026, ASCE 7 is expected in 2028, and IBC code publication in 2030. To achieve these timelines, USGS must plan ahead. The current outline was developed in 2019, a four year advance in USGS scientists' data and product development was requested in 2020. Between 2020 and 2023, these scientists shared ongoing work, including draft versions of the seismic model, with user groups for early feedback to better refine the final products. USGS participates in ASCE 7-28 committees to familiarize engineers with the new data during the standards adoption process.

After USGS data and models are incorporated into ASCE standards, USGS has to deliver the final products to ASCE, a process that takes up to a year. Data delivery includes creating a referenced DOI for inclusion in ASCE 7, a geodatabase that provides a locked version of the data

[3] BSSC, under contract with the FEMA, develops and maintains a key resource — the *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures* that are used in ASCE 7 (BSSC, No Date)

adopted in the ASCE standard as well as a backup access point, and web services that link the geodatabase and ASCE 7 Hazard Tool.

3.2.2. NIST: Wind and Tornado Hazard

NIST develops wind hazard maps for both non-tornadic and tornadic winds. The work is accomplished through discretionary funding of NIST projects and associated contracts and grants. Economic analysis by the NIST Office of Applied Economics aids the adoption of standards into model codes.

The NIST mission is to promote US innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve quality of life. NIST has more than 40 years of experience studying building fire and structural failures. More than forty NIST-led investigations and failure studies have been conducted since 1969 and have resulted in more than 40 significant changes to building codes and design guidelines. NIST's disaster and failure studies focus on establishing the likely technical factors for damage or failure as well as injuries and fatalities. NIST studies are documented in technical reports for consideration by relevant national building and fire model codes, standards, and/or practices. Examples include the 2011 Joplin tornado that led to consideration of how the building envelope of critical buildings performed during tornado events, which led to the development of tornado wind load criteria for ASCE 7, and the ongoing investigation of the Hurricane Maria disaster in Puerto Rico that is studying critical facility performance and their dependence on infrastructure. NIST's Office of Applied Economics provides economic analysis that assists engineers and standards developers to assess costs and benefits. This analysis is useful when standards are proposed for adoption into codes, including IBC model codes.

The NIST process to develop wind and tornado hazard maps for ASCE 7 was accomplished through a combination of internal research and development (R&D), contracts, and research grants. NIST workshops for stakeholder engagement and feedback help to identify key issues with products and fix them before they reach users. The process to develop non-hurricane wind hazard maps for ASCE 7-16 was through NIST's internal R&D and is based on observed wind speed at weather stations. Hazard curves for thunderstorms and non-thunderstorm winds are developed separately for each station, combined, and gridded estimates are produced for multiple return periods. The decision to focus on peak 3-second wind gusts was done to enhance public understanding, because that is the duration of gust typically reported to the public by meteorologists.

For hurricane (tropical cyclone) wind speeds, there is a lack of sufficient data available from wind recording sites, so modeling is needed based on large scale predictors such as sea surface temperature. Hurricane and non-hurricane wind speeds are combined into final "basic wind speed" hazard maps. Tornado wind hazards are treated separately from the basic wind speed. The process to develop tornado hazard maps for ASCE 7-22 is illustrated in Figure 3.2.2. ASCE 7-22 is the first version where tornado wind hazard has been incorporated into maps for engineering users.

NIST R&D is currently supporting the development of future condition wind and tornado hazard maps. NIST collaborates with the ASCE 7 Wind Load Sub-Committee to confirm technical approaches and approve final maps. There is also collaboration with the ASCE 7 Load Combinations Sub-Committee on reliability analyses to determine appropriate return periods for wind hazards, as well as other hazards affected by future climate conditions.

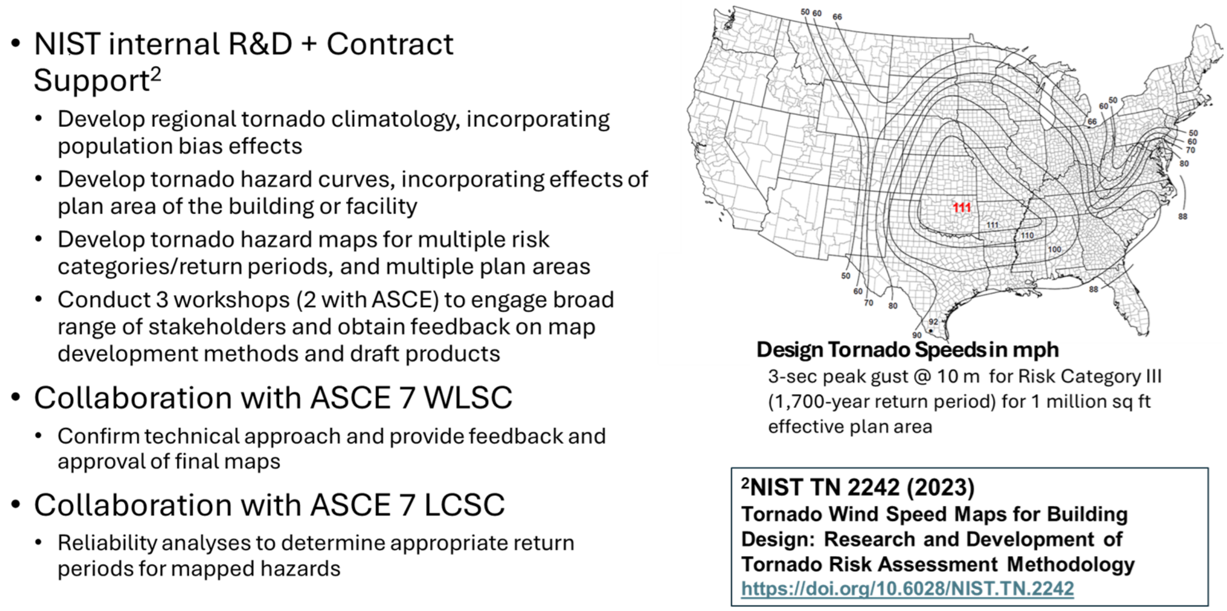

Figure 3.2.2 NIST Process to Develop Tornado Hazard Maps for ASCE 7-22. Tornado wind hazard maps were a newly quantified hazard in the 2022 update of the ASCE 7 standard. NIST's process includes the use of internal research and development, working with contractors, and the use of workshops to engage stakeholders and get feedback on methods and draft products. Collaboration with ASCE is through membership on load committees including the Wind Load Sub-Committee (WLSC) and the Load Combinations Sub-Committee (LCSC) and published as a NIST Technical Note (Goupil, J., Rezaeian, S., McAllister, T., Ingargiola, J., and Wei, Y., 2024).

NIST held workshops to identify leading climate resilience practices that communities are using, including flooding, sea level rise, and wildfire, and is documented in a NIST report (https://doi.org/10.6028/NIST.GCR.24-056). NIST is also developing a roadmap to identify gaps and set up a framework moving forward for incorporating climate data into codes and standards. Grants and cooperative agreements are in progress to help in quantifying the risk and impact of wind and hailstorms in a warming climate and quantifying non-stationary tornado risk in a warming climate among others. NIST participates in the ASCE-NOAA Task Force collaboration with hopes of improved collaboration mechanisms among Federal agencies.

3.2.3. FEMA – Flood Hazard

FEMA creates flood hazard maps under the National Flood Insurance Program (NFIP) that are referenced in ASCE standards. Federal discretionary funding and flat fees on NFIP policies provide support, but there is no long-term funding source. FEMA Future Flood Risk Data (FFRD) will be probabilistic, not binary for flood risk, and include climate projections and sea level rise. FEMA closely collaborated on ASCE 7-22 Supplement 2 (Flood Supplement) and the

ASCE 24 update. ASCE is planning to incorporate FEMA Flood hazard mapping into the ASCE Hazard Tool.

The FEMA mission is to help people before, during, and after disasters. The mission identifies resilience as a critical component, and the agency is pivoting to enhance this aspect of FEMA. The 2024 FEMA theme is "Resilience - for buildings, people, and communities." The priorities are to increase all-hazards resilience; better serve underserved communities; deepen coordination within FEMA and across Federal agencies; work with Federal partners to identify shared requirements and avoid redundant funding; and advance building codes across the Federal government.

The FEMA Flood Map Service Center is the official online platform for all flood hazard mapping products created under the NFIP. This is the official link for ASCE 7. The FFRD development is ongoing at FEMA. Annual funding comes from congressional discretionary funds and flat discretionary fees with no long-term funding source. FFRD will be probabilistic, not binary, and will include more flood characteristics such as depth of flow and velocity and waves and depth and flow in addition to impacts of future climate and sea level rise. FEMA is piloting new ways of visualizing and accessing FEMA FFRD maps. This would aid developments in ASCE 7 flood standards (e.g., multiple recurrence intervals).

FEMA participates in ASCE 7 and ASCE 24 and the update cycles for these two standards are being brought into sync. The latest revision to ASCE 7-22 (Supplement 2) and ASCE 24 represents the biggest advancement to flood maps in 20 years. FEMA also participates in ASCE 7-28 including the future conditions chapter. The ASCE Hazard Tool will eventually include FEMA flood data to improve accessibility for engineers. There is a need for continued flood research on coasts and elsewhere and incorporation into standards development.

3.2.4. NOAA and ASCE: Tsunami Hazard

NOAA developed probabilistic Tsunami Design Zone (TDZ) maps for ASCE 7-16 and their continued update and integration into ASCE 7-22 and ASCE 7-28. ASCE leadership was essential for combining interdisciplinary groups into a cohesive partnership. TDZ maps had initial funding from SEI and COPRI with NOAA in-kind contributions. The upgrade to high-resolution maps was funded through a combination of state funds, NOAA Coastal Zone Management funds, and state-managed NOAA National Tsunami Hazard Mitigation Project (NTHMP) funds. Completion of maps for US territories is a priority.

NOAA's Pacific Marine Environmental Laboratory (PMEL) collaborates with the ASCE 7 Tsunami Loads and Effects Subcommittee to develop tsunami hazard maps for use in ASCE standards. This includes the development of original probabilistic TDZ maps for five Pacific states for ASCE 7-16 tsunami provisions and geodatabase, and the high-resolution TDZ maps for Hawaii to update the ASCE 7-22 and 7-28 provisions and geodatabase. Multiple challenges were encountered in the collaboration.

The first challenge was that the ASCE committee represents diverse backgrounds leading to unfamiliarity with the process and expectations of ASCE standards development. The exceptional and dedicated leadership from ASCE helped combine interdisciplinary groups into a cohesive partnership. The second challenge was the enormous map coverage to be delivered in a short period of time. The team made a smart team decision on low-resolution of 60 meters instead of high-resolution of 10 meters for the initial maps. The process relied on NOAA's support in high-performance computing and extra labor and committee support in map illustration. The third challenge was the funding resource. The team had timely SEI and COPRI sponsorship and funding. The fourth challenge was the sustainability of code development, especially of the high-resolution map updates after ASCE 7-16. The team is working towards a high-resolution mapping for all US western coastlines and relying heavily on NOAA support, along with state funding and state-managed grants from NOAA.

The importance of providing hazard maps for US territories was emphasized. Guam has some maps developed but has not been integrated into code yet. For Puerto Rico and the greater Caribbean area, work has not been done yet. The team would need support from ASCE, NOAA, or state partners to accomplish that work.

Opportunities that arise include the coordination in the development of standards between ASCE and states through NOAA's NTHMP. NOAA PMEL has developed collaborative relationships with other federal agencies (e.g., Department of State), NOAA line offices, Navy, States (Hawaii and Washington), and industry partners, which have resulted in award-winning designs and demonstrated success.

3.2.5. Panel Discussion

When asked what worked best in their relationship with ASCE, the presenters listed the following:

- USGS's continuous relation with ASCE 7 helps to improve from cycle to cycle and to justify the work to Congress to continue funding. Coordination could still be improved as ASCE often needs more time to review seismic models, and update cycles do not always coincide due to funding constraints.
- NIST cites a good understanding between NIST and ASCE about what each party brings to the table, understanding what ASCE needs for code development, and ASCE knowing NIST has the research capacity to support needs.
- FEMA mentions that their building disaster support program assessment teams include engineers who are members of the ASCE standards committees who can provide evidence of the need for changes to the standards committees. FEMA also contributes expertise in bringing standards into the international model codes.
- NOAA PMEL notes that support through state initiatives has led to successful funding and encourages code development and adoption and noted a desire for the ASCE-NOAA Task Force to include tsunami hazards in future work.

A clear message emerged that finding a method of obtaining synchronous, continuous long-term funding (such as the NEHRP model) would be ideal to address all hazards. NEHRP is a model for success because they have continuous funding from four agencies with defined tasks and levels of funding. However, the complexity of agency capabilities and mandates makes it difficult to streamline the funding. High-visibility engagement, directly addressing

Congressional priorities, and continued justification of the use of funding to Congress helps maintain funding continuity. A primary justification for NEHRP is that the seismic hazard maps developed through NEHRP funding are used and referenced in building codes.

To reduce risk, standards need to be adopted into building codes. FEMA emphasized that fewer than half of communities have building codes that are based off of a flood model. Yet the role of Federal agencies in developing standards and in the adoption of building codes is constrained. Federal agencies contribute critical science and engineering research and the development of data products, but Federal partners do not represent agencies when attending industry events, nor should Federal agencies be pushing a consensus. However, participation on committees provides useful feedback on the usefulness of Federal agency data products. Outreach on training in the use of data products and other technical matters is also critical. Recordings of this panel and other presentations are in Appendix B.

3.3. Lunch and Learn: Do Global Warming Levels Solve Climate Uncertainty?

In order to design for future conditions, engineers need a way to characterize future climate that is: scientifically justified, usable within the capacity of practicing engineers, straightforward enough to be adopted into engineering standards, and easy to communicate (to engineers or with clients) – particularly regarding relative risk levels. The choice should also be durable and flexible as climate science moves forward, given long life cycles of standards and code adoption. This presentation looked at the use of Global Warming Level (GWL) as an alternative to emissions scenarios to accomplish these goals. In addition, the choice of GWL to define future climates has direct implications for how climate services should be designed.

GWL is the change in globally averaged temperature at or near the surface *relative to a baseline period*, typically taken as the 1850-1900 "early industrial" average. The Earth is currently at a GWL of about 1.2 – 1.3 °C. Recent estimates suggest that there is a roughly 50% chance of exceeding 3°C by the year 2100[4].

[4] This statement is based on IPCC AR6 Working Group III estimate that SSP3-7.0 (labeled as "Current Policy") has a 78% chance of exceeding 3°C (IPCC,2022), a 2023 report by UNEP that states "A continuation of the level of climate change mitigation efforts implied by current policies is estimated to limit global warming to 3°C (range: 1.9–3.8°C) throughout the century with a 66 percent chance" (United Nations Environment Programme, 2023), and the 2023 analysis from the Climate Action Tracker that estimates a 50% chance of exceeding 2.7 °C, and hence a lower than 50% chance of exceeding 3°C (Climate Action Tracker, 2023).

Global Warming Level Summary

GWL is the change in global average surface temperature relative to a baseline period usually taken as 1850-1900. GWL is a key indicator of the overall amount that the global climate has changed. Most of the observed warming has occurred since 1950, and the rate of change has accelerated this century. GWL is increasingly being used to integrate information across multiple climate models and scenarios by both the scientific community and the climate impacts community. ASCE 7-28 proposes to use a 3℃ GWL by the 2080-2100 period to characterize future conditions.

The GWL approach is based on the same sets of climate model output as the more traditional emissions scenario approach. GWL can be easily calculated from the output of any climate model and for any emissions scenarios. In the 2030s when climate science has moved on to CMIP8 (presuming that CMIP phases continue at the same cadence as in the past) with two more generations of emissions scenarios compared to present, it will still be possible to characterize future climates in terms of GWL. By being scenario neutral, this approach allows civil engineers to be confident that a given design will provide a reasonable level of resilience, regardless of how atmospheric chemistry evolves due to changes in actual GHG emissions.

Many environmental hazards are approximately well-scaled with GWL without reference to when that GWL occurs (Arias et al., 2021). An example of a hazard that scales well is heavy precipitation over land areas. Though the reasons for this scaling relationship are complex, one reason for its existence is that increasing heavy precipitation is a consequence of increasing atmospheric water vapor, which itself is closely tied to the overall magnitude of global warming. There are some "slow variables" such as sea level rise (SLR) where the *rate of change* is dependent on GWL rather than the total magnitude of change. Sea level rise is a cumulative process with the rate of change proportional to the uptake of heat into the oceans and the melting of land ice. For these slow variables both GWL and a time span are needed to get an accurate scaling relationship.

The use of GWLs does not eliminate uncertainty or even reduce the overall uncertainty. Rather, it is a way to "refactor" uncertainty, separating questions of global policy and implementation from the physical climate questions of how a given GWL might manifest locally or regionally (see Figure 3.3).

Characterizing the future climate in terms of GWL has become much more common in scientific literature, and it is gaining traction in climate adaptation as well (Seneviratne et al., 2021). ASCE 7-28 is proposing to use a 3°C GWL by the time period of 2080-2100 as the nominal future condition to guide design for structural loads. The recent 2022 interagency sea level rise report (Sweet et al., 2022) also screened global sea level scenario according to GWLs and provided a table that cross-references SLR scenarios to equivalent ranges of GWLs in the year 2100. By knowing the equivalent GWL, other climate variables, such as the frequency of extreme precipitation, can be aligned in a consistent way with a choice of SLR scenario.

While there are many advantages, the use of GWL does not solve all problems regarding future uncertainty. Climate models can produce different spatial patterns of regional change despite having the same change in global average temperature. Thus, there remains considerable regional uncertainty for a given GWL. Some quantities in some locations have a large uncertainty even in the direction of change, depending on the climate model used to get the projection, so that GWL gives little information about the likely change. Other caveats include if there is a strong regional or local climate driver such as urbanization or land use change that is not correlated with GWL or if the response variable is highly nonlinear, such as is the case with snowpack where above some GWL there will simply be no snow in some locations.

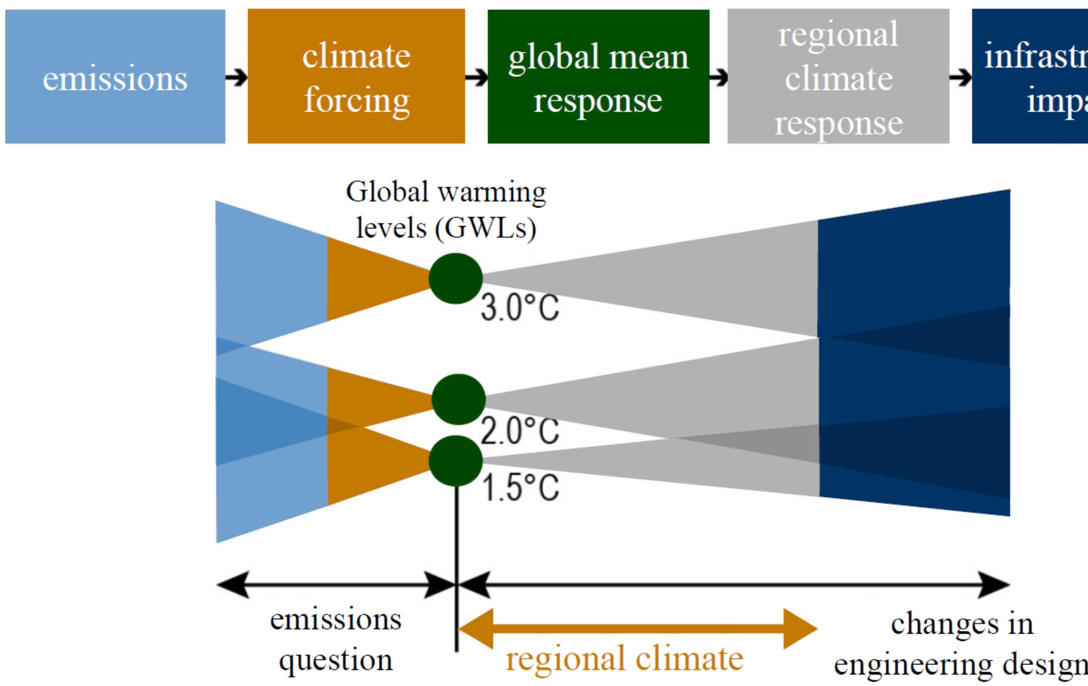

Figure 3.3 Use of GWLs Connecting Emissions to Impact Questions. The framing of GWLs changing the starting point of the chain of events from emissions to infrastructure impacts, but as the figure depicts there is still a range of changes needed in the engineering design based on the variety of regional climate outcomes (Modified from Cross-Chapter Box 11.1 from Seneviratne et al., 2021).

4. Climate Hazard Needs and Priorities

The summary that follows reflects the contributions, expertise, and viewpoints of the workshop participants expressed during the breakout sessions as synthesized by the authors of this report.

A variety of climate and weather processes and associated hydrologic processes can constitute a hazard to the function of engineered structures and systems. Many of these are expected to demonstrate nonstationary behavior in the future in response to a warming world. In an effort to develop a robust compilation of engineering use cases and specific description of climate data or data products needed to address each, the 2024 workshop attendees participated in six hazard-centric breakouts. The breakout discussions are summarized below in the form of both a table of climate information needs and a written description of key opportunities and challenges in each area. Key points are provided for each type of hazard, and a cross-cutting summary is presented at the end.

4.1. Introduction

The 2022 and 2024 workshops are guided by the practice-to-practice approach (Figure 4.1). The current use of weather, climate, and hydrologic information in engineering practice is the starting point, with the relevant engineering applications noted broadly as use cases. The goal of the breakout sessions was not to create a detailed specification of climate data needs, which would not have been possible given the 90 minutes allotted. Rather the goal was to determine the general characteristics of the data needs so that more focused efforts could be made to specify data products.

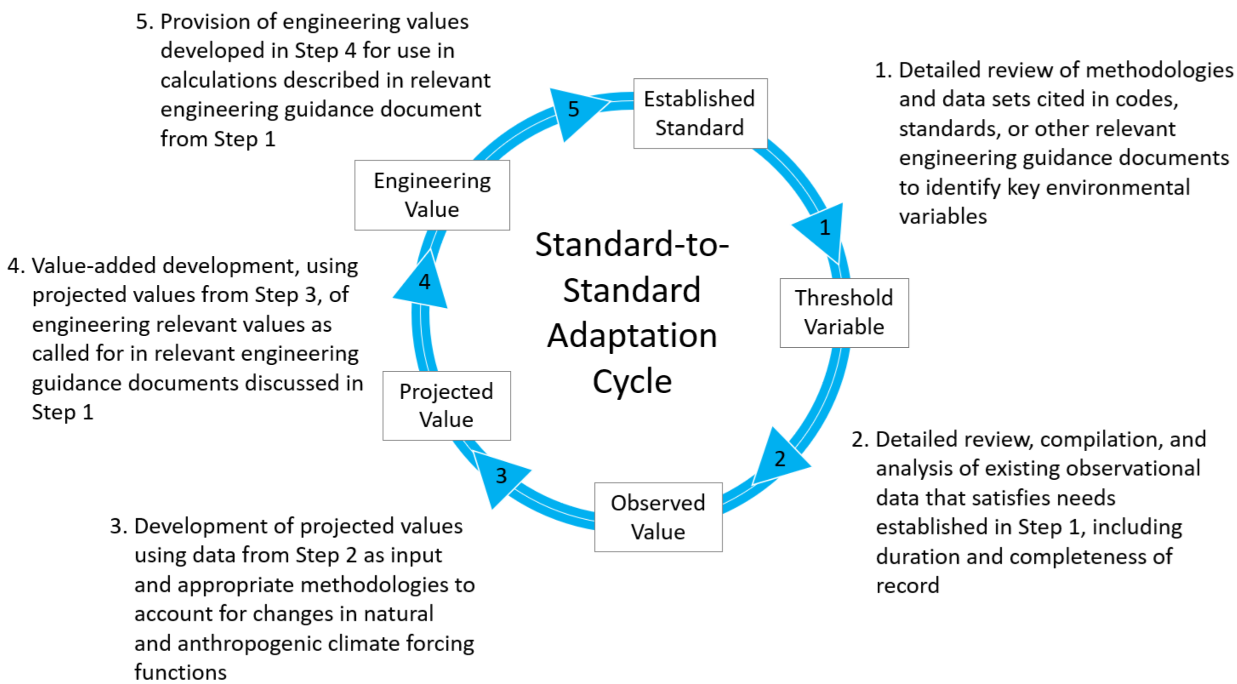

Figure 4.1 Practice-to-Practice Cycle. The cycle explains the feedback loop of determining the scientific data needed for the engineering standards (Walker and DeAngelo, 2024).

4.1.1. How to Read Tables

Each breakout group was instructed to focus their discussions on filling out the "Table of Priority Needs" for their type of environmental hazard in real-time during the session. The breakout participants identified specific topics related to the overall hazard type of the session. These topics related to engineering standards, MOPs, or other common use cases seen by practicing engineers that are known to be sensitive to climate change. The engineering values related to the environmental hazard – that is, the quantities that an engineer uses in their analysis and that directly supports the use case – were noted, as well as how these might be changing. Finally, the climate, weather, hydrologic, and other environmental inputs used in that analysis were listed, including the variables (temperature, precipitation, etc.), statistical treatment (means, annual exceedance probability (AEP) values, etc.) and other characteristics of the needed data.

Utilizing the recordings, breakout facilitators and the report lead author filled in gaps in the tables. The use case column was intended as a flexible category to capture the varied ways in which engineering standards practice incorporate data about environmental hazards.

The columns on the table reflect an idealized conception of how climate and weather information is used in engineering practice that is depicted in Figure 4.1.1. In this conceptual model, climate and weather (and often hydrologic) data is used to derive quantities that an engineer uses in their analysis that are relevant to some environmental hazard. This whole chain of analysis supports the use case. A use case may be a calculation or procedure specified in a standard (e.g., calculating wind loading), a more general design problem related to an environmental hazard (e.g., designing infrastructure on degrading permafrost or in areas prone to coastal flooding), or even the development of the next generation of standards and MOPs. Other environmental and non-environmental inputs may inform the use case, and understanding this context would help in providing usable climate and weather data.

NOAA and other weather and climate science organizations provide the foundational datasets that form the climate inputs. The development and provision of data that is useful to practicing engineers is done in a variety of ways. In some cases, engineers download weather and climate data and perform their own calculations. An example is calculating air freezing index (AFI) from a local weather station that is not in NOAA's database. Alternatively, the values such as the 0.01 AEP of precipitation from NOAA Atlas 14 are primarily the product of government and academic scientists. In other cases, the data used by practicing engineers is primarily the product of research engineers and statisticians (e.g., reliability-based snow loads for ASCE 7) who need access to a much larger set of weather and climate data than would the practicing engineer who is referencing that standard. This "middle ground" at the boundary between weather and climate science and engineering demands co-production to be effective, and it is largely this "middle ground" that was the topic of discussion in the breakout sessions.

The various breakouts approached the columns of the tables in different ways. Where there are differences in interpretation, it is best to focus on the overall flow of information and data from climate, weather, and hydrologic observations and models, through intermediate quantities used by engineers to address an environmental hazard, with the goal of supporting an engineering calculation, analysis, or design use case.

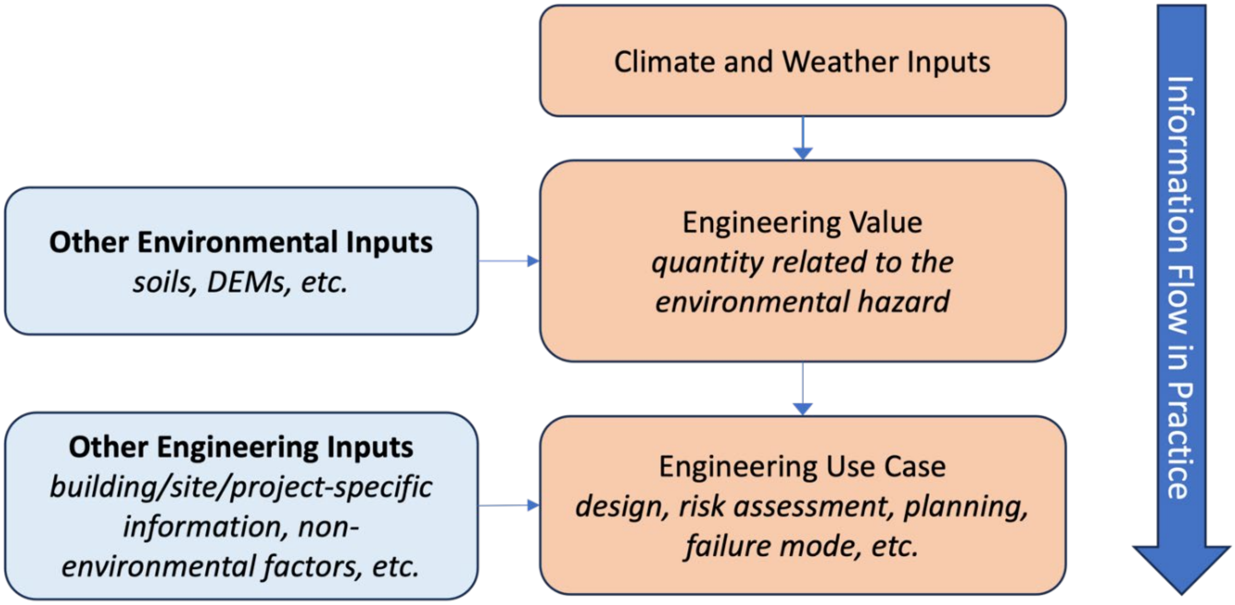

Figure 4.1.1 Information Flow between Engineering and Environmental Factors. The practice-to-practice approach first requires that we understand the use of weather and climate data in the current practice. The breakout sessions first identified engineering uses relevant to the category environmental hazard they were assigned. For each use case, they worked "upstream" in the information flow to determine the quantities related to these hazards that engineers use in their analysis, and the climate and weather inputs needed to derive those values. The practice-to-practice approach then asks how to obtain these climate and weather inputs in a changing climate – that is, how to estimate the future environmental conditions relevant to the engineering use case.

This report's "use cases" for each hazard breakout have been grouped thematically where possible. A detailed rubric that provides our working definitions for the table columns is in Appendix D. Abbreviated tables focused on these thematic groups are provided in this section, with the full tables in Appendix D. A blank entry in the table merely indicates that it was not discussed in the breakout session and does not imply that no information exists.

4.2. Breakout: Extreme Temperatures, Emphasis on Cold Regions

4.2.1. Background

Key Points in Extreme Temperatures: Emphasis on Cold Regions:
• Cold regions engineers are already dealing with the impacts of a warming climate. • Air Freezing Index (AFI) and Air Thawing Index (ATI) were identified in both the 2022 and 2024 workshops as relevant to many use cases in cold regions, particularly for below-ground hazards. • For above-ground hazards, the range of extreme temperatures to which building materials are exposed and the frequency of freeze-thaw cycles may provide useful information to engineers. • Climate data used to compute the surface energy budgets would aid in thermal management of soils and permafrost.

The 2022 ASCE-NOAA workshops discussed temperature extremes in ASCE standards. The primary findings were that there were relatively few quantitative metrics of temperature specified in ASCE standards. Two standards that were noted were ASCE 32 and ASCE 21. Instead, temperature often appeared with other environmental variables, sometimes qualitatively and sometimes linked to decision tools external to the ASCE standards. Following on the identification of needs during the 2022 ASCE-NOAA Task Force workshops, funding has become available to support work by NOAA in producing updated products for the Air Freezing Index (ASCE 32) and 50-year return (2% AEP) daily maximum temperature (ASCE 21). It was noted that temperature change was likely to have the greatest relevance as a primary hazard for cold regions engineering.

The purpose of this breakout was to go beyond those two ASCE standards to include MOPs and other common engineering use cases, with explicit inclusion of cold regions engineering needs. The Cold Regions Utility Monograph (Smith et al., 1996, also referred to as the Cold Regions Utility Manual) is in the process of being updated and includes many calculations that depend on temperature. Temperature-sensitive topics in the manual include water treatment, piping, and thermal design for permafrost regions.

The use cases and specific temperature-related environmental hazards discussed in the breakout session are summarized in Table 4.1 and the complete "Table of Priority Needs" is available in the appendix. Three thematic sections follow the below table: below-ground hazards, including soils and permafrost, above-ground hazards to exposed materials and structures, and other hazards. The "other hazards" include those that were poorly defined in the discussions, were treated in other breakouts, or were beyond the scope of this workshop but may be suitable as future workshop topics. ***Temperature*** refers to near-surface ambient air temperature unless otherwise noted.

Table 4.2.1 Temperature Breakout Summary

	Use Cases Discussed	Environmental Hazards	Climate and Weather Variables	ASCE Guidance Documents
Sub-surface including Soils and Permafrost	• Piping, pipelines • Water treatment • Thermal design in permafrost regions • Building foundation design • Pavement	• Depth of permafrost active layer • Depth of frost penetration • Frost heave • Thaw weakening	• Air Freezing Index • Design Air Freezing Index • Mean Return Period Air Freezing Index • Air Thawing Index • Daily average temperature • Snow cover • Humidity (air) • Rainfall • Wind speed	• ASCE 32 • *Cold Regions Utilities Monograph* • *Frost Action in Soils*
Exposed Materials and Structures	• Construction material expansion, performance, degradation • Building enclosure design, incl. facades and roofing • Heat exchanger efficiency • Utility lines	• Excessive high temperature and temperature range • Excessive humidity • Freeze-thaw cycles	• Daily max. and min. air temperature • Range of extreme temperatures • Number of freeze-thaw cycles • Air thawing index • AEP for minimum temperature	• ASCE 21 • Other standards*

	Use Cases Discussed	Environmental Hazards	Climate and Weather Variables	ASCE Guidance Documents
	• Transportation	• Extreme or prolonged cold temperature	• Long-term average temperature • Water temperature	
Water Temperature	• Design in coastal regions • Bridge abutment design • Ecological applications • Water treatment	• High water temperature • Icing, frazil ice, ice loading	• Air temperature • Air thawing index • Cumulative freezing degree days • Water temperature at multiple depths • Ice depth (on water)	• No specific documents discussed

*Civil engineers and architects use standards from American Concrete Institute (ACI), ASTM, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and other organizations that use temperature and other environmental data.

4.2.2. Use Cases: Temperature and Below-Ground Hazards

Cold regions are seeing rapid warming with degradation of permafrost, changing soil characteristics including frost depth, a decrease in cold extremes, and an increase in warm extremes. The number of freeze-thaw cycles are also changing in many locations. For sites on permafrost, the changing Depth of the Active Layer is the key concern that cuts across several use cases. Both AFI defined as degree days below freezing during a climatological cold season and its complement, the Air Thawing Index (ATI), were seen as the primary climate information required. There was discussion of thermal management "keeping the ground frozen" including such practices as installation of thermosyphons, increasing the albedo of the surface by "painting it white," vegetation management, and management of snow cover. For these practices, a more complete description of the surface energy budget is desired and thus a more complete suite of meteorological variables is required for engineering analyses.

For permafrost-free cold regions, many of the same concerns and data needs are present including for the AFI and ATI. The interaction between water in the soil column and the depth of frost penetration was noted with dry soils allowing greater frost penetration in the winter. The influence of soil and ground water in cold regions was also discussed in the earth materials breakout. Cold regions in North America have generally seen greater warming in the wintertime than in the summertime, and the importance of having the seasonal differences in warming taken into account in any projections was strongly noted.

While the focus was on use cases in cold regions, the discussion also included several examples of hot extremes, and changing temperature fluctuations that have impacts outside cold regions. Temperature influences drought. For example, soil water content can induce shear stresses in soils that are hazardous to foundations, underground utilities, and other underground installations. In addition, temperature influences water in the soil column, which impacts slope stability and the bearing capacity of soils. The breakout on Earth Materials deals in greater detail with soil properties.

4.2.3. Use Cases: Temperature and Exposed Materials and Structures

Changing temperatures also presents hazards above ground. There were several use cases centered around the performance and degradation of materials. The exposure of materials to freeze-thaw cycles can damage building materials. This may be an emerging hazard in regions that have historically stayed frozen most of the winter but are experiencing an increasing number of cycles as the climate warms. The use cases include the choice of materials for building envelopes. This hazard may be particularly critical for historic structures where the choice of building materials was not adequately resistant to freeze-thaw cycles.

Changes in extreme temperatures were also seen as important for the performance of building materials such as sealants and adhesives. Increasing humidity along with increasing temperatures was seen as a particular concern. Relative humidity (RH) was mentioned as a primary variable, so an understanding of whether RH significantly changes as temperatures warm is desired.

Thermal expansion and contraction of materials in the design and performance of building envelopes was seen as another temperature-sensitive use-case. The range of ambient air temperature (characterized by the extremes of the daily minimum and daily maximum temperature) was seen as a critical weather variable that is likely to change in the future. This hazard is related not only to the range of maximum relative to minimum extremes but also relative to the temperatures at which the materials were installed. While the temperature of the material itself is often the design variable, there was a request for change in ambient air temperature as the most relevant input.

There was extensive discussion of the effect of freeze-thaw cycles on concrete as an example of potential material degradation under changing conditions. Materials such as concrete are subjected to extensive testing by societies such as ASTM and the ACI. The standards, specifications, and other guidelines published by these organizations are used by engineers and architects to select appropriate building materials based on their performance under the range of environmental conditions that the material will be exposed to. While the testing standards may not change, the engineer or architect will need to anticipate future environmental conditions. However, it was unclear what the preferred quantitative metric of freeze-thaw would be, if any. One avenue to pursue might be for ASCE or another entity to coordinate with ACI or ASTM to determine quantitative environmental (rather than laboratory) metrics for freeze-thaw cycles.

4.2.4. Discussion

Changing water temperature was also seen as a potential climate change hazard for multiple engineering disciplines and use cases including environmental, coastal, and water treatment. Air temperature was seen as a critical variable, particularly where detailed observations of water temperature are not available. The interaction with ice (sea, lake, and river ice) was also noted. However, there was not time for detailed discussion on this topic, and the complex interaction of air and water temperature with water ice as well as with bacteriological loads (for water quality) put it beyond the scope of this workshop.

The relationship of temperature to wildfire was also discussed. Several characteristics of desired data were noted. Most prominent was a map of changing wildfire risk. Given the complexity of wildfire risk, it too was beyond the scope of this workshop. The above examples could be topics for future exploration.

4.3. Breakout: Rainfall Extremes Especially with Respect to Stormwater and Flood Design

4.3.1. Background

> Key Points for Rainfall Extremes Especially with Respect to Stormwater and Flood Design:
>
> - NOAA Atlas 15 volumes 1 (historical non-stationary analysis) and 2 (projections) will likely meet the needs of ASCE 7 roof load calculations, both present day and projected, though perhaps not in time for direct inclusion in ASCE 7-28.
> - Stormwater control would benefit from 5-minute rainfall estimates to be provided in Atlas 15.
> - Some engineers are turning to radar-based estimates such as the gridded Multi-Radar, Multi Sensor (MRMS) product for short duration rainfall events.
> - A need was expressed for consistent sets of multiple input variables that comprise the surface water and energy budgets to support hydrologic and hydraulic modeling.

The workshops held in 2022 helped to establish a firm need for the accelerated development of NOAA Atlas 15 to support environmental hazard loads used in ASCE 7-28. In particular, there is a need for projections of heavy precipitation that would support the future conditions chapter (Chapter 36) of ASCE 7-28. Other use cases were also discussed, including developing a greater understanding of changes in PMP. In both cases, NOAA has responded to the articulated needs, such that the phased release of Atlas 15 can inform development of future environmental loads in ASCE 7-28, and a research agenda has been developed to update national PMP estimates (NOAA, No Date; National Academies, 2024).

The 2024 breakout was scoped to build on the previous workshop focusing primarily on two aspects of rainfall hazard in engineering. The first is the development of data to support the ASCE 7 update cycle beyond the ASCE 7-28 iteration, including the application to ASCE 24 (Flood Resistant Design). The second is to investigate the needs for stormwater management and other use cases. The discussions in this breakout overlap with other sessions, notably Compound Flooding and Snow.

Table 4.3.1 Rainfall Breakout Summary

	Use Cases Discussed	Environmental Hazards	Climate and Weather Variables	ASCE Guidance Documents
Building External Loads	• Roof failure due to surcharge of secondary drainage • Fluvial flooding • Rain on snow roof loading and inundation	• Hydrostatic load • Hydrodynamic load • Rain on snow	• 15-minute precipitation rate • Flood hydrograph for detailed hydro. modeling • SWE (see Snow breakout)	• ASCE 7 • ASCE 24
Stormwater Control	• Highway, road, street flooding • Watercourse pollution • Urban stormwater system design • Sewerage design • Combined sewer overflows • Erosion Control	• Peak rate of discharge • Inflow hydrology • Heavy rainfall event	• 5- through 60-minute rainfall rates • Design storm of record • Soil moisture • Cumulative Intensity-Duration-Frequency (IDF) curves (point and watershed)	• ASCE 12 • ASCE 33 • ASCE 45 • ASCE 62 • ASCE 66 • ASCE 68 • ASCE MOP 77 • ASCE MOP 153
Hydrologic and Hydraulic Modeling	• Fluvial flooding leading to structural failure • Inundation of streets, buildings, roads • Hydraulic modeling (HEC-RAS, SWMM)	• Area of inundation • Depth, volume duration of flooding	• Inputs for H&H modeling • Cumulative IDF curves (point and watershed) • Gridded sub-hourly precipitation • Relative humidity, temperature, evapotranspiration	• ASCE 12 • ASCE 24 • ASCE 33 • ASCE 34 • ASCE 56 • ASCE 57 • ASCE 62
	• Reservoir Operations • Flood – controlled release	• As above	• Design storm events • Sub-hourly precipitation (watershed)	• ASCE 40*
Reservoir Operations in Flood and Drought	• Water supply for reservoir ops. during flood • Sedimentation at outlet • Water Supply during drought	• High flow with flooding potential • Precipitation drought • Low flow hydrology	• Gridded precipitation in near real-time • Precipitation forecasts for FIRO† • Projections of FIRO climate variables	• ASCE 40*

*Civil engineers often use guidance documents from federal agencies including Reclamation, United States Army Corps of Engineers (USACE) and Bureau of Land Management (BLM) for these use cases.
†Forecast Informed Reservoir Operations (FIRO) (see text)

4.3.2. Use Cases: Building External Loads

The need for 15-minute precipitation rates with respect to roof loads (ASCE 7§8[5]) has been articulated by SEI and will be met by the publication of Atlas 15 Volumes 1 and 2, though the timing of publication of Atlas 15 may not be optimal for inclusion in the current update cycle (ASCE 7-28). Changes in the probability of rain on snow was flagged as a hazard for consideration, represented as a combination load in ASCE 7§2. The actual data requirement will still pull from Atlas 15 and is further discussed in the Snow breakout. Hydrodynamic loads from

[5] The rainfall hazard section references chapters within ASCE standards using the § symbol.

flooding, calculated from water levels and flow rates (ASCE 24, ASCE 7§5) draw from FEMA inundation maps or from specifically designed hydraulic models.

4.3.3. Use Cases: Stormwater Control

It was noted that many mandated design levels come from Federal design standards that have been adopted locally. This is reflected in, e.g., ASCE 45§4 and ASCE 65§8, and reporting that typical design return periods in the literature are 2-15 years in residential areas, and 10-100 years in commercial and high-value districts, and for roads that are used for emergency service delivery. Participants identified that the NOAA MRMS 1 kilometer gridded observation data are utilized for simulating the storm of record. However, some commonly used stormwater models that are preferred by some jurisdictions use only point estimates of precipitation. Participants were enthusiastic about the spatial scale but *expressed a need for the shorter temporal scales (5-15 minute) that are under development*. Some discussion centered around the *research need to support changes in the areal reduction factor and time-to-concentration* in response to projected changes in the spatial scale, duration, and overall volume of precipitation in intense storms. The greatest challenges were identified in coastal areas where extreme rainfall occurs in combination with high tides in coastal areas, identifying a need for improved compound flooding guidance. See Compound Flooding breakout for more discussion on this topic.

4.3.4. Hydrological and Hydraulic Models

Engineers run both hydrologic and hydraulic models for the purpose of water supply, reservoir management, determining the potential for flooding inundation, design of urban stormwater systems, and other applications. The climate and weather data needs for running these models were discussed.

In addition to precipitation, inputs include hourly temperatures, relative humidity, and dew point temperature (or evaporation and evapotranspiration). The provision of these inputs would aid in the development of digital twins[6] of stormwater collection systems to simulate their performance during storms of record.

Data from multiple sources may be needed, and participants observed that *land use and landcover data are supplied by USGS with an irregular (suboptimal) update frequency*, affecting river flow estimates used in designs for irrigation, hydropower, and water supply. Participants noted the *need for consistency in data product formats t*o enable modelers to build tools that work in conjunction with those data. In many cases, however, participants also noted that engineers utilize a single hyetograph developed from Atlas 14 or occasionally MRMS quantitative precipitation estimates, due to the lack of updated guidance from regulatory agencies. "However, guidance from local jurisdictions or regulatory agencies may limit the types of precipitation data that can be used."

[6] "'Digital twins' are virtual representations of physical objects, processes, or systems... A digital twin is used to predict how changes may affect its physical counterpart" (GAO, 2023).

4.3.5. Use Case: Reservoir Operations

While dam design relies on PMP estimates, there is also a need for improved real-time and seasonal forecasting to support reservoir operations. Many federally maintained reservoirs are primarily operated for water supply and flood control with some additional authorized storage use (e.g., recreation and fisheries). Thus, there is a need for watershed scale information at longer (multiday/seasonal) temporal scales to assess the risk of overtopping during spring rain-on-snow flood conditions versus debris accumulations at outlets following drought. While the daily operations benefit from NOAA operational forecast models (Forecast Informed Reservoir Operations or FIRO), forward planning needs to consider the potential for multiple consecutive storms and associated flooding.

4.3.6. Discussion

Many of the above use cases are not under the complete purview of ASCE standards or MOPs. For instance, urban stormwater drainage is mandated locally. However, participants expressed a desire for clear, unified guidance on how to incorporate climate change into designs. This may take the form of new or updated ASCE Manuals of Practice and guidance documents. It would also be beneficial for NOAA to coordinate with other Federal agencies, particularly those that fund infrastructure and climate resilience projects, to ensure that methods and approaches being promoted by ASCE are consistent with requirements across Federal agencies.

Considering the needs for future research, green infrastructure design (and associated water quality output) could benefit from better information that separates rainfall statistics based on different types of storms. Participants requested more detailed information and support on how to include the uncertainty in climate projections into their risk-based design. In particular, they raised the suggestion for engineered failure to accommodate the economic limitations in managing risks from extreme rainfall. Benefit Cost Analysis (BCA) (such as that required for certain FEMA grants) also requires improved guidance to account for climate change and adaptation induced changes in risk to better assess the benefits from mitigation strategies.

4.4. Breakout: Snow Loads, including Rain-on-Snow Loads

Key Points for Snow Loads, including Rain-on-Snow Loads:

- Validation of gridded snow products is a key concern.
- Projections of snow in regions of high topographic relief such as the western United States will require change factors at a high spatial resolution, whereas areas of lower topographic relief may be amenable to regionalized change factors
- A product that includes the duration of snow water equivalent (SWE) at several thresholds would have multiple uses
- Access to projections of daily SWE combined with hourly or sub-hourly rainfall would allow an improvement in the calculation of rain on snow loads
- Projections of ice deposition on structures require considerable post-processing of climate model output because precipitation phase (ice, freezing rain, etc.) is not well simulated at GCM scales.

4.4.1. Background

The breakout began with a summary of the treatment of snow loads in ASCE 7 – both current and prospective including the challenges in obtaining and validating SWE from climate models for this purpose. The proposed language in ASCE 7-28 chapter 36 modifies the ground snow load to consider a future-conditions ground snow load. The future condition ground snow load is proposed to be determined by using an adjustment factor, or scale factor, applied to the ground snow load requirements currently available in Chapter 7 of ASCE 7, which do not consider the effects of climate change.

Ideally, for the purposes of ASCE 7, daily SWE would be provided directly as part of GCM or Regional Climate Model (RCM) output. This would allow for straightforward calculations of annual maximum SWE as required for the ASCE 7 probability calculations. Other options for deriving SWE include forcing snow-specific energy balance models, such as a Variable Infiltration Capacity (VIC) with downscaled and bias corrected GCM outputs.

Regardless of how SWE estimates are calculated, there remain at least two main challenges for the use of future projection SWE in engineering design. The first challenge involves the spatial resolution of GCM output. Many GCMs run at a more than 50 kilometer resolution, which oversimplifies the complex topography of western United States. It is not practical to use GCM-derived SWE values in their native resolution for engineering design in locations where snow accumulation patterns are known to change rapidly over short distances. This means that any future projection of SWE will require statistical or dynamical downscaling of GCM model runs to an ideal spatial resolution of one to 4 kilometers. Nonetheless, GCMs and RCMs have systematic biases in their snow output that need to be accounted for.

The second challenge involves the validation of future projections of SWE. Because SWE is a second order variable in GCMs (if available at all at daily timescales), there has been less validation of SWE output as compared to primary GCM variables like temperature and precipitation. Further, the number of high-fidelity measurements of SWE that could be used to validate GCM output are limited and mainly confined to the SNOpack TELemetry (SNOTEL) station network in western United States. Some concerns regarding SWE bias may be mitigated by focusing only on changes in model-derived SWE in hindcast versus future periods, rather than trying to directly use model-derived SWE values in design. That said, there remains the need to understand what trends in future projection SWE can be attributed to real-climate effects as opposed to artifacts of the snow modeling approach.

Table 4.4.1 Snow Breakout Summary

	Use Cases Discussed	Environmental Hazard	Climate and Weather Variables	ASCE Guidance Documents
ASCE 7 Snow Load	• Basic snow load • Drifting snow load • Snow in Combined structural loads • Rain on snow • Reliability-based standard • Development of future standards	• Peak snow load on ground (i.e., peak snow load) • Peak snow load with drift • Combined load from rain and snow	• Snow water equivalent (SWE) (maximum annual, whole distribution) • Winter wind parameter • SWE duration • SWE (daily values), sub-hourly rainfall coincident with daily SWE	• ASCE 7*
ASCE7 Ice Load	• Ice load calculation in ASCE 7 (current and proposed) • Ice deposition on structures and transmission lines	• Freezing rain amount and duration • Ice thickness on structure	• Precipitation amount and phase (daily or sub-daily) • Concurrent temperature, wind, dewpoint T • Atm. profile of humidity and temperature (empirical methods)	• ASCE 7* • ASCE MOP 74
Other	• Cold regions-multiple	• Heat flux into ground	• Snow cover • Snow depth	• See temperature breakout
	• Water resources	• Heavy runoff from snowpack • Low runoff from declining snowpack	• SWE along with full surface energy and water balance.	• No specific documents discussed

*Discussion of ASCE 7 snow loads focused on potential improvements for the 2028 and future update cycles

4.4.2. Use Case: ASCE 7 Snow Loads Including Drifting Snow

The key snow-related design variable in ASCE 7 is the weight of accumulated snow on the roof of a structure. This quantity is referred to as the design roof snow load, which is derived from probabilistic characterizations of the annual maximum SWE of settled snow on the ground. The design value is derived from a reliability analysis that requires characterization of the entire upper tail of the annual maximum SWE rather than relying on a single, return period or AEP.

Roof load provisions in Chapter 7 of ASCE 7 include specifications for unbalanced snow loads resulting from drifted snow, nearly all of which are a function of the design ground snow load.

Given this engineering context, the primary snow-related quantity of interest in future climate projections is annual maximum ground SWE. A secondary variable of interest is winter wind speeds, as required to calculate snow drifts. Note that snow load and drifted snow calculations from ASCE 7 propagate to FEMA documents used in BCA. While the duration of snow load is not used for the basic snow load calculation, it was noted that the duration is relevant for designs using some structural materials (wood) but not others (steel) due to the differing characteristic of the materials.

4.4.3. Use Case: ASCE 7 Rain on Snow

Rain on snow (ROS) is seen as an increasing hazard in some cold regions due to warming conditions and due to the increased intensity of heavy rainfall though perhaps a decreasing hazard in other areas where large snowpacks become rarer. The ROS load is typically calculated using the snow at an "arbitrary point in time" (APT). Given a suite of variables that include daily SWE and hourly precipitation, the changing frequency and severity of ROS events – relevant to roof loads – could be estimated.

One critical question is whether or not the water content of rain falling on the snowpack is already reflected in the SWE model outputs. This question is difficult to answer since the characterization of ROS as part of, or separate from, the measured snowpack is likely model dependent. This is a question that could be asked of those who provide snow data from climate models as well as more specific hydrologic models that simulate snow.

4.4.4. Use Case: ASCE 7 Snow in Combined Loads

Currently, snow loads are combined with other loads using a single fixed ratio of peak loads. While perhaps a longer-term goal, it is also useful for estimates of the spatially varying duration of snow at specified thresholds to take into account the different snow climatologies of different areas. For this reason, it is desirable to have access to the duration of snow load, not just the extremal values.

Understanding the duration of the snow load is key to potential updates to load combinations, which combine other environmental hazards (such as earthquakes and wind) with snow at APT. Climate change promises to change both the extreme snow load and the APT load. While short term research is focusing on extreme snow loads, APT snow loads must be considered when thinking about future projections of load combinations. A useful product might contain the duration of snow loads at various thresholds.

4.4.5. Use Case: Ice Loading-Freezing Rain

While snow loads were the main topic of discussion, ice loading on structures was also discussed. The presence of freezing rain that leads to ice deposition is noted in weather observations, but for locations far from an hourly weather observation station, it is typically estimated using empirical relationships with temperature and humidity profiles of the atmosphere. This is also the approach taken with climate models. Weather and climate data needs for ice loading as identified by the ASCE 7-28 future conditions subcommittee has led to a collaboration that has received funding from NIST to look at projections of freezing rain. Therefore, some of the data needs listed in this section may be addressed but unlikely in time for full inclusion in ASCE 7-28.

4.4.6. Other Topics

The role of snow cover as it relates to heat flux into and out of the ground was discussed in relation to thermal management in regions of permafrost and also in relation to frost depth in non-permafrost cold regions. A more general consideration of precipitation phase (rain, snow, freezing rain, hail, etc.) and how that might change in the future was brought up in several contexts including the important role played by snowpack in water resources/water supply in western US. The potential for increased freezing rain or rain on snow in coastal Alaska was of particular concern. These topics were also discussed in other breakouts including Temperature and Compound Flooding.

4.4.7. Discussion

As noted above, validation of snow products based on climate models is of paramount importance. Validation is hampered by the fact that the primary snow monitoring network in the western U.S. was designed for water resources management and not for snow hazard analysis. SNOTEL stations are located within a very narrow elevation band where few people live and few structures are built. Understanding the changing snow hazard in cities and towns where the primary snow hazard is due to rare but large events, and validating models in such locations is therefore difficult.

In western U.S., it was noted that regional change factors would be inadequate as they neglect strong topographic effects. Changes in snow in areas with less prominent topography, including much of central and eastern U.S., might be more amenable to regional analyses of change factors. The question of climate model resolution was discussed, and recent work showing that as models go to finer resolutions (of about 25 kilometers) the representation of snow improves.

4.5. Breakout: Wind and Related Design Responses

Key Points for Wind and Related Design Responses:

- Improved accessibility of existing and future observed wind data with improved curation of metadata would aid in the update of standards and the detection of trends.
- Increased resolution for climate projections would particularly help with extratropical storm winds but introduces new sources of uncertainty.
- Engineers have more confidence in projected tropical storm wind hazard than in thunderstorm or tornado winds.
- Provision of the proxy variables used to estimate tropical cyclones, as well as those that could be used for thunderstorm and tornado winds would streamline the process of development of projections for these hazards.
- Mooring of ships and design of piers and wharves following the DOD UFC 4-152-01 standard uses 30-second gust speeds and has unique considerations due to the difference in winds over land and sea.

4.5.1. Background

ASCE 7 is focused on one key wind variable: a wind gust with an averaging time of 3 seconds at 33 feet (10 meters) height in open terrain. This "basic wind speed" is determined by combining wind speed extremes from tropical cyclone (TC, also referred to as hurricane), extratropical cyclone (synoptic), and thunderstorm (mesoscale systems) storm types. The principal design variable used in the calculation of wind loading on structures is this basic wind speed, with different AEP values (recurrence intervals) specified for different risk categories of building. Tornadic winds are handled separately and were first included in ASCE 7-22 in a separate chapter.

Risk categories (RC) are assigned based on the criticality of the structure, and the significance of the consequence should a failure occur. For example, hospitals (RC IV) and schools (RC III) are treated with higher safety margins than typical buildings (RC II). This risk categorization plays a key role in determining design standards, especially in the face of uncertain windstorm frequencies and magnitudes in a changing climate, where climate change forcing impacts each meteorological phenomenon differently, and where the confidence in climate change's fingerprints on each phenomena varies.

Historically, engineers have relied on stationary data, using measures such as mean recurrence intervals for wind hazard assessments. Historically, design codes have focused on peak wind speeds over short intervals, like 3-second gusts, without considering changes in the frequency or duration of wind events. With accelerating climate change trends, especially in temperature and potentially in wind, a stationary approach may no longer be sufficient. With evidence suggesting that tornadoes, storms, and other extreme events may be occurring more frequently or with changing footprints, the question arises: should frequency and duration also be integrated into the standards? Given the evolving knowledge in this area, the challenge is determining when the confidence level is sufficient to include non-stationarity into design standards for each of the storm types and how to balance historical data with future projections in updated hazard maps.

A poll of the breakout participants indicated that TC are regarded as the most important windstorm forcing mode for structures; mesoscale systems (thunderstorm winds) and tornadoes are the storm modes most in need of research to improve engineering-based information. The climate scientists in the group expressed less confidence in the quality of model projections of TC wind speeds than engineers. Both engineers and climate scientists agree that a climate change scenario around 3˚C, as proposed for ASCE 7-28, is appropriate for use in engineering planning.

The discussion focused on data needs for those who are developing the maps and datasets of design wind speeds for future updates of ASCE 7. The end product delivered to practicing engineers are the basic wind speed and tornado wind speed design values for different RCs. Development of hazard maps for each storm type is treated as a separate use case. Additional use cases were also briefly discussed, including maritime applications, and are mentioned below.

Table 4.5.1 Wind Breakout Summary

	Use Cases Discussed	**Environmental Hazard**	**Climate and Weather Variables**	**ASCE Guidance Documents**
ASCE 7 Wind Loads	• Wind load calculation in ASCE 7	• Basic (Non-Tornado) Wind	• Basic Wind Speed: peak 3-second gust at 10 m height over open terrain • Hourly Wind Speed • Temperature • Pressure at surface	• ASCE 7
	• Development of Basic Wind hazard map	• Tropical Cyclone	• 850 hectopascal, 250 hectopascal level winds • Temperature at surface and tropopause • Pressure at all levels	
	• Development of Basic Wind hazard map	• Extratropical Storm	• Wind speed and direction at 10- m • Turbulent Kinetic Energy (TKE)	
	• Development of Basic Wind hazard map	• Thunderstorm	• TKE • Vertical wind shear • CAPE • CIN • Lifted Index • Dewpoint Depression	
	• Development of Tornado hazard map	• Tornado (ASCE 7-22 and later)	• Similar to those for thunderstorm	
Other Wind Use Cases	• Naval Facility Design • Berthing and mooring of ships • Transmission Lines (wind loading on structure) • Wind and Wave Analysis/Modeling • Building Facade Performance	• Wind load on structures and their components • Wind-driven waves and currents	• 30-second gust at 10 meter height, 25-year mean return interval or longer • Basic Wind Speed from ASCE 7 • Duration of wind above threshold values	• ASCE 7 • ASCE MOP 74 • ASCE MOP *Design Standards for Piers and Wharves* (under development) • Department of Defense Unified Facilities Criteria (UFC 4-152-01)

4.5.2. Use Case: ASCE 7 Tropical Cyclone (Hurricane) Wind Hazard Map

There is emerging confidence that Atlantic TCs are becoming less frequent but individually stronger, strengthening rapidly near landfall, and extending their impacts farther inland. TC wind hazard maps are currently determined using an empirical/statistical hurricane track model applied to observed data. The model accounts for key large-scale parameters including sea surface temperature (SST), tropopause temperature, and winds at different levels in the atmosphere and a gradient wind approximation when near landfall. Data is then converted to a standard 3-second gust at 10-m height. Large numbers of synthetic storms can be simulated to estimate the statistics of rare events. Future hurricane wind statistics could be estimated by using GCM estimates of the changes in the key parameters. SST is expected to increase, though other parameters are less certain in their effects. There is the potential for slower movement of hurricanes under climate change, and thus longer exposure to hurricane-force winds. Using projections from GCMs in combination with statistical meteorologic methods and engineering models helps quantify uncertainty and leads engineers to have more confidence in future risk assessment for hurricane-prone areas than for regions where thunderstorm and tornado hazards dominate.

4.5.3. Use Case: ASCE 7 Extratropical (Synoptic) Storm Wind Hazard Map

The topic of extratropical storm winds is relatively underexplored in the U.S., particularly in comparison to recent European and Canadian efforts. Despite the available technology, the US has not made significant advancements in studying these storms, at least as related to engineering applications. This lack of progress is possibly due to a lack of perceived urgency or sufficient data. Whereas severe convective storms often dominate the largest extremes, extratropical storms are drivers of more frequent (though somewhat less extreme) wind-related events in the northern US. Extratropical storms are generally shifting northward and undergoing other changes impacting their felt effects. Currently, extratropical storm wind speeds are estimated from historical observations at weather stations. Challenges in using the observational record include limited data on short-duration wind gusts and difficulty in capturing storm frequency and behavior, especially in mountainous regions. Wind direction was also mentioned as another key parameter because of local topographic and other effects that may lead to preferential directions for extreme winds.

Climate modelers have more confidence in the simulations and projections of extratropical storms than for the other storm types. However, the estimate of extreme windspeeds from GCMs involves an understanding of turbulent kinetic energy in the atmospheric boundary layer which is not directly simulated in GCMs but rather parameterized. Small scale topographic effects are also not well modeled at typical GCM scales. (approximately 100 kilometer (km) resolution). Higher-resolution simulations like North America CORDEX or more recent 25-km GCM simulations could help improve understanding of these dynamics.

4.5.4. Use Case: Developing ASCE 7 Thunderstorm Wind Hazard Map

Thunderstorm winds are currently estimated from observed winds when thunderstorms are present. There is less understanding currently about how thunderstorms may change in the future. Research has focused on how the large-scale atmospheric environment affects thunderstorm characteristics. The participants mentioned quantities such as Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) along with other parameters that are known to influence the scale and strength of thunderstorm winds. The effect of climate change on thunderstorms and in particular on mesoscale systems is the subject of ongoing research, and their corresponding wind speed changes are uncertain.

4.5.5. Use Case: ASCE 7 Tornado Winds

There are multi-decadal trends in tornado patterns with increases in the Southeast United States and decreases in the traditional central US "Tornado Alley." However, the evidence for this spatial shift is not always consistent. There is a large uncertainty about future tornado winds due to limitations on historical data as well as the difficulty in modeling tornado wind processes. This difficulty is primarily due to large spatial scale of the GCMs and RCMs compared to that of tornadic thunderstorms and tornadoes. As with thunderstorms, research has focused on large scale environmental parameters that are related to the probability of tornado formation and to the types of organized convection that lead to tornadoes, with corresponding data needs.

4.5.6. Use Case: Mooring of Ships/Pier and Wharf Design

The design and evaluation of mooring systems for ships in extreme weather conditions was discussed. This includes designing facilities for the US Navy, including piers and wharves. The Unified Facilities Criteria (UFC 4-152-01) was mentioned as the guidance document for this application. As noted in section 2, ASCE is developing a manual of practice on *Design Standards for Piers and Wharves*. Design is guided by the 30-second wind gust with return intervals of 25 years or longer. Wind from the land may behave differently than from the sea. For example, the Durst Curve, a model used to adjust wind speed data, applies differently based on exposure categories. Storm duration is also a factor with dominant storm type (e.g., hurricanes, thunderstorms) affecting duration. Wind-wave modeling was also discussed in this context.

4.5.7. Other Use Cases

Wind also causes loading on transmission lines that is dealt with in the ASCE MOP 74 (Guidelines for Electrical Transmission Line Structural Loading). The ASCE 7 basic wind speed was referenced for this application. For building façade performance, it was noted that the duration of wind above threshold values may be a relevant variable though no specific standard was identified.

4.5.8. Discussion

Maintaining and improving the quality and consistency of observational data will aid the process of updating standards and in the future estimate of climate change trends and impacts on wind hazards. Properly storing, curating, and maintaining long-term climate datasets include extending wind observations at least 10-20 more years in the future and properly curating the data with detailed metadata such as anemometer heights and station locations. Improving the quality and accessibility of ASOS and other existing wind data is a high priority to aid in updating standards.

The participants discussed challenges with some statistical methods used to estimate the design winds. Issues that were identified include the potential over-estimation of extremes at very long return periods (very low AEP), the potential confusion of changes in event frequency with changes in the largest magnitude events, and the role of regionalization of parameters (smoothing of the maps). It was put forward that these issues become more problematic when considering non-stationarity.

Higher spatial and temporal resolution is essential for better projections, particularly for synoptic winds and thunderstorm winds, but it introduces technical challenges of data management and processing power. Higher-resolution models and downscaling methods may also introduce new sources of uncertainty and bias that may lead to unrealistic estimates of large-magnitude, low-probability extremes needed for design. The group suggested using multiple approaches for quantifying uncertainty, combined with detailed process studies for each storm type. Future efforts might also involve coordinated modeling and collaboration across disciplines to create reliable, high-resolution projections that can inform both near- and long-term designs.

Finally, the actual service life of buildings and infrastructures can be much longer than 50 years, and clients are increasingly requesting longer design lifespans, particularly for critical facilities like hospitals, schools, and water infrastructure, where a 100-year service life is becoming common. A longer design life increases the sensitivity to poorly sampled low-frequency but high-amplitude events and allows for a wider range of potential climate futures depending on the evolution of greenhouse gas emissions, increasing the uncertainty. This variability in service life expectations complicates the uniform application of climate data across different infrastructure types, and it suggests a need for updated reliability-based design loads that consider future climate projections alongside historical data.

4.6. Changes in Earth Material Behavior, Related to Temperature and Precipitation

Key Points for Changes in Earth Material Behavior, Related to Temperature and Precipitation:

- Changes to groundwater elevation were seen as a key hazard across multiple use cases.
- Both increasing (flooding, liquefaction, structural loading) and decreasing groundwater elevation (subsidence and shear stresses) were seen as hazards.
- Assessing the changing risk of mass movement of earth and rock, due to groundwater, precipitation, vegetation and other land surface characteristics, was seen as a priority use case
- Changes in permafrost and frost heave were critical in cold regions.

4.6.1. Background

The breakout on earth material response to changing conditions was the first time that geotechnical and related disciplines were involved in the ASCE-NOAA Task Force workshops. The G-I relies less on standards and MOPs than other ASCE institutes. However, a framework document is under development to provide more systematic guidance for geotechnical applications than currently exist at ASCE.

The individual hazards and use cases discussed during the 2024 workshop were placed into four main categories: the effects of groundwater changes on structural loads, mass movement of rock and soils, changes specific to cold regions (permafrost degradation and frost heave), and land subsidence.

Table 4.6.1 Changes in Earth Material Behavior Breakout Summary

	Use Cases Discussed	Environmental Hazards	Climate and Weather Variables	ASCE Guidance Documents
Groundwater Effects on Structural Loads	• Lateral Groundwater Loading • Uplift or buoyancy loading • Soil Liquefaction (seismic design)	• Changing GW elevation, surface aquifer extent, discharge/recharge	• Seasonal precipitation • Sea Level Rise (coastal locations) • Soil moisture and type	• ASCE 7 • ASCE 45,46, 47
Mass Movement of Rock and Soils	• Earth slide and flows • Debris slides, flows and floods • Rockslide	• Changing GW elevation • Increased freeze-thaw cycles • Water pore pressure • Vegetation change • Long-term drought • Wildfire • Major precipitation event	• Seasonal to inter-annual precipitation • Heavy precipitation events • Daily min. and max. temperature • Insolation	• No specific documents discussed
Frost Heave and Permafrost Degradation	• Thermal modeling • Conductive heat transfer across surface • Buried utilities • Large-scale infrastructure	• Changing GW elevation • Decreasing Air Freezing Index • Increasing average air temperature • Changing water flow patterns • Depth of Permafrost Active Layer	• Daily air temperature • Total precipitation • Snow • Soil moisture and soil type • Wind speed and direction at 3 m	• ASCE 32 • *Cold Regions Utilities Monograph*
Land Subsidence	• Buried utilities • Large-scale infrastructure	• Changing GW elevation, aquifer recharge • Increasing Effective Stress in soils	• Seasonal to interannual precipitation	• No specific documents discussed

4.6.2. Use Case: Effects of Groundwater on Structural Loads

Three specific effects of groundwater on structures were discussed in relation to the ASCE 7 standard – lateral loads, buoyancy loads, and soil liquefaction. All three referenced groundwater elevation (or water table depth) as the primary environmental parameter and in particular the highest groundwater elevation (closest to surface or at surface) observed over time. Water infrastructure design, as well as basement design of buildings, often requires determining where the seasonal high water table is located. Current practice typically relies on measurements of the groundwater table at or near the project site to determine this.

For future climate conditions, some type of modeling of groundwater would be needed. Understanding the empirical relationship between monthly or seasonal precipitation and groundwater variations was discussed as a possibility. If such a relationship were established, then future projections of precipitation could be used to generate projections of groundwater elevation changes.

4.6.3. Use Case: Mass Movement of Rock and Soils

One geotechnical engineer suggested that changing landslide hazard was perhaps the "number one Geotech/climate issue." The environmental factors influencing landslides are complex. However, the observed and projected increase in intense rainfall events was identified as a key climate parameter. Seasonal precipitation changes were also identified as these can pre-condition a slope. Other landscape changes due to vegetation change, often mediated by wildfire, were mentioned. As both factors are related to climatic drivers, they were considered in this report. Finally, freeze-thaw cycles were related to rockfall.

4.6.4. Use Case: Frost Heave, Permafrost Degradation

Cold regions experience specific earth materials challenges related to permafrost degradation and to frost penetration in permafrost free areas. The discussions in the earth materials breakout focused on the role of groundwater and on modeling/managing the surface heat flux to preserve frozen conditions below ground. Particular climatic variables that were mentioned as relevant to future surface heat fluxes in addition to temperature were snow cover and 3 meter wind speed and direction. Soil moisture influences the thermal properties of soil. There are, however, no standards related to permafrost degradation.

4.6.5. Other Use Cases, Including Land Subsidence

Land subsidence due to both drought and aquifer drawdown was discussed. The potential for increased groundwater extraction as a response to aridification and the potential for reduced groundwater recharge were seen as the main climate-change related drivers. Groundwater elevation is a key parameter. The potential for increased drought was seen as leading to changes in soil stresses as well as to land subsidence.

Erosion was discussed in several contexts. Coastal and inland erosion along rivers was discussed in the Compound Flooding breakout and was discussed in this breakout as well. One additional factor was the possibility of large, qualitative changes in land surface properties due to both mass movement of earth (landslides) and erosion of soils due to overland flow and other results of increases in heavy precipitation (aspects of this were discussed in the Rainfall breakout).

4.6.6. Discussion

Changes in groundwater levels (e.g., the elevation of the water table and other characteristics of groundwater) are a key driver of geotechnical hazards in the future. The impact on structural loads, such as the buoyancy effects on walls, is significant. Because procedures for estimating this are detailed in ASCE 7, providing groundwater change data that could be used in these calculations could be a good place to start. It was noted that in practice these risks are mitigated through proper drainage, so drainage design and maintenance are critical use cases.

Groundwater changes can have impacts on regional scales, such as near the coast where sea level rise (and saltwater intrusion) raises the water table, as well as in regions of aquifer drawdown that lead to land subsidence. Sea level rise projections are available for the U.S. coasts. Understanding the needs for practicing engineers dealing with coastal aquifers would help define more specific data products. Groundwater also is relevant for frost heave and for the penetration of cold into the soil column.

Estimating water table changes has received less attention in the global climate modeling community than other parameters such as soil moisture content. The water table is a difficult quantity for climate models to model with precision. Numerical groundwater flow models are computationally intensive, and that process is not included in global climate and earth system models. It was suggested that an empirical modeling approach might be feasible. Seasonal precipitation values could be related to water table variations to give an empirical estimate of water table elevation. Precipitation projections could be used to estimate future water table changes under climate change scenarios. While that is one possible approach, more research is likely needed on this topic.

Precipitation on multiple time scales is also a critical climate and weather input. Monthly to seasonal average precipitation is related to groundwater recharge and soil water content, while heavy precipitation events (presumably 15-minute to hourly to storm event total) were also identified as important for understanding future erosion and mass movement. The interaction between groundwater and heavy precipitation in generating flooding (discussed in Compound Flooding breakout) is significant. NOAA Atlas 15 will address some of these data needs, but a more comprehensive needs assessment would be desirable.

4.7. Breakout: Compound Flooding Including Inland and Coastal Flooding

Key Points for Compound Flooding Including Inland and Coastal Flooding:

- The primary data need for compound flooding is for consistent data across the relevant flooding processes at locations where processes interact. This may require data traditionally collected and published by multiple agencies.
- Coastal sites require consistent tidal stage (including sea level rise), storm surge, and wind wave data, including between tide gauges. Selected locations (e.g., coastal cities and estuary environments) may also require information regarding precipitation and river stage/flow.
- Coordinating the data for heavy precipitation and pluvial and fluvial effects (e.g., flooding on rivers/streams and in urban environments) would be useful for estimating flooding hazards in inland environment.

4.7.1. Background

Compound flooding occurs due to the combined effects of more than one flood-causing process, such as precipitation-induced river discharge and storm surge. These flood-causing processes may be induced by the same event (e.g., hurricanes) or result from independent phenomena occurring concurrently or in relatively close succession.

The compound flooding breakout participants focused on various combinations of flooding processes and their respective data needs. It should be noted that a MOP that addresses several aspects of compound flooding is under development. For all the use cases, the severity, duration, and frequency of hazards (including joint hazard frequency) were seen as relevant. Severity measures discussed included water levels, inundation depths and extent, and flow velocities along with the effects of erosion, soil saturation, and groundwater. Observational and synthetic data needs were discussed during the breakout session.

Participants also discussed the challenges associated with selecting compound flooding “design values” for use in conjunction with engineering applications, which may involve selecting specific combinations of hazard severities (e.g., rainfall depths and coastal water levels) from among many possible combinations with the same specified frequency of exceedance along a hazard surface contour.

Table 4.7.1 Compound Flooding Breakout Summary

	Use Cases Discussed*	Environmental Hazards	Climate and Weather Variables	ASCE Guidance Documents
Coastal Compound Flooding	• Design of structures and infrastructure in coastal areas	• Coastal water levels or inundation depth/extent as well as wave heights and water velocity • Precipitation leading to pluvial or fluvial flooding • River flooding (discharge, stage, velocities) and inundation extent • Groundwater-exacerbated flooding	• Tidal water levels, including tides and storm surge (non-tidal residuals)-observed and modeled with synthetic TCs • Relative Sea Level Rise scenarios • Wave heights and velocity – observed and modeled with synthetic TCs • Precipitation depths and durations • River discharge, stage, velocities • Groundwater level	• ASCE Compound Flooding MOP (under development)
Urban Flooding	• Design of urban stormwater and drainage systems • Design of structures and infrastructure in urban settings	• Heavy rainfall exceeding drainage system capacity • Heavy rainfall exceeding storage capacity in reservoirs and soils • Groundwater-exacerbated flooding • High water level submerging outfall	• Precipitation (high spatial and temporal resolution) • Soil storage capacity (soil moisture) • Water table depth • Reservoir levels and storage capacities • Water level at outfalls (SLR, surge, tides, etc., if coastal, river/lake level if inland) • Precipitation, temperature, ET, soil moisture for modeling soil storage and groundwater	• No specific documents discussed
Inland Compound Flooding (tributary)	• Design of structures and infrastructure near rivers/streams	• Flooding at river confluences	• River discharge, stage, velocity for tributaries, main stem, and at/below confluences	• No specific documents discussed
Compound Flooding on Inland Lakes (e.g., Great Lakes)	• Design of structures and infrastructure near inland lakes	• Similar considerations to compound coastal flooding	• Similar considerations to coastal (ocean) compound flooding above.	• No specific documents discussed
Other Hazards		• Erosion	• Water levels, velocities, waves, etc., as above • Additional information on land cover change, soil types, erosion potential	• No specific documents discussed
	• Design of structures and infrastructure near rivers/streams	• Rain on snow flooding	• Precipitation, temperature, snowpack, antecedent river discharge	• See rainfall breakout

* The compound flooding breakout discussions focused primarily on characterizing the environmental hazard due to multiple flood-generating processes rather than focusing on specific use cases.

4.7.2. Use Case: Coastal Compound Flooding

Compound flooding in coastal areas can result from the interaction of many processes that affect coastal water level and inundation of adjacent areas. Coastal hazards that lead to compound flooding include tidal water levels and the effects of relative sea level rise, storm surge, and waves. Participants identified the need for coastal water level information at a higher spatial resolution and at a consistent temporal resolution, particularly in areas where multiple processes may be involved (e.g., in estuary environments and near tidally influenced rivers where there is an interaction of fluvial and coastal processes). However, one participant expressed concern that lumping too many processes together might slow progress in dealing with the triad of tidal level, storm surge, and waves and that solidifying progress on these oceanic hazards is needed particularly for locations between tide gauges.

The Interagency Sea Level Rise Technical Report (Sweet et al., 2022) is a critical resource for the tidal component. NOAA's upcoming Coastal Ocean Reanalysis (CORA) for the Gulf of Mexico and the East Coast of the United States will provide 500-meter resolution, hourly historical water levels, including the effects of storm surge, and an estimate of wave characteristics (Rose et al., 2024). A preliminary version has been released.

Inland flooding mechanisms, such as river discharge, heavy precipitation events, and groundwater changes, can be a hazard in themselves in coastal regions and can also interact with coastal processes. Obtaining river stage between gauges and in tidally influenced areas was a high priority but viewed as challenging. Obtaining river levels in these areas would likely need hydraulic/hydrologic modeling and data regarding basin-wide precipitation and downstream conditions. Lake flooding, and in particular large lake flooding such as on the shores of the Great Lakes, involves similar data needs as coastal (oceanic) flooding.

4.7.3. Use Case: Urban Flooding

The breakout participants discussed data needs for flooding in urban settings due to heavy rainfall exceeding the capacity of urban drainage and storage systems. Urban flooding use cases typically need precipitation data or statistics at sub-hourly temporal resolution, sometimes down to five-minute resolution. Satellite remote sensing and weather radar were put forward as ways to achieve the high spatial and temporal resolution historical data that is desired in urban areas.

One compounding effect is the capacity of storage systems and water level at the outlet of drainage systems, be it a lake/reservoir, river, estuary, or the ocean. Higher water levels at outlets may lead to backflow and reduced capacity, leading to localized flooding in locations depending on drainage systems. Urban flooding can occur in coastal cities (e.g., due to tropical cyclones), further compounding coastal hazards.

Another compounding effect is groundwater that can act to reduce the storage capacity of the soils or interact with drainage systems. These compounding effects were also discussed in the Rainfall breakout, including the hazard due to controlled release from reservoirs, which is a contributor to fluvial flooding along rivers/streams. The multiple time scales involved make this a challenging problem.

4.7.4. Other Use Cases and Hazards

Flooding at river confluences and rain on snow flooding were also discussed, which require the coordination of weather and climate information from multiple sources. The topic of erosion – which can result from multiple processes – was also discussed, though not in detail.

4.7.5. Discussion

The breakout participants emphasized a continued need for a clear definition of compound flooding, including the types of compound flooding. The data needs for compound flooding hazard assessment are driven by the specific hazards being analyzed in a particular combination. The specification of the parameters that need to be measured (in the case of observational data) or generated/extracted (in the case of synthetic/modeled/reanalyzed data) is driven by hazard-specific considerations and varies by location.

For compound hazards, multiple variables measured or generated/extracted at the same location (or in close proximity) and with similar temporal resolution are needed. Current observational gauges tend to be in places that allow for measuring a single process. However, compound hazards require data measured in more complex environments, such as where the processes interact and are not necessarily separable. In addition, it was noted that there may be a lack of clarity regarding jurisdiction for collection or generation of data when multiple processes are involved (e.g., coastal water levels versus river flow), with different agencies historically being responsible for data associated with different processes.

Synthetic data typically involves augmenting the observational sample at a given location or generating a sample where observations are not available using simulations/models. The intent is to generate synthetic data that is consistent with the properties (or expected properties) of observational data. For example, a model may be used to develop an augmented catalog of historical storms through storm displacement or stochastic methods. These storms can then be run through hydrodynamic models to determine water levels. The process of generating synthetic water level and wave data can be modified to include scenarios of climate change, as has been done in the USGS wave climatology product.

The specific data needs for compound hazards stem from ensuring adequate and consistent spatial and temporal resolution of those data series. In coastal regions, participants noted that fine scale (e.g., 500-meter) is desired to characterize the present-day water levels, etc. using synthetic data-generating processes. However, it was recognized that the pattern of the change in climatic inputs (or our ability to spatially characterize those changes) may be significantly coarser. In many instances, a 25-kilometer resolution was deemed acceptable, which is a resolution achieved by regional climate models and some global climate models. It was noted that urban areas require closer to 5-kilometer (or less) resolution and a 5-minute temporal scale. In general, however, a 15-minute temporal scale was noted as a good default. Reanalysis products (such as NOAA's CORA) will provide historical estimates at 500 meter spatial resolution.

The above discussion focuses primarily on the development of datasets that can be used to inform statistical or other hazard assessments. However, during the breakout session, a distinction was made between two broad classes of data needs associated with compound flooding hazards. The first is the need for raw (or minimally processed) data needs (e.g., time series) that would be required to support independent assessments or the development of joint probabilities and other derived products that might be needed by practicing engineers (i.e., as discussed above). The second is the need for processed data such as compound hazard curves and surfaces (similar to the processed results provided for NOAA Atlas 14/15, but for co-occurring hazards) and model results such as inundation depths and spatial extent that would be required for practical engineering needs.

4.8. Cross-cutting Climate Data Needs

The purpose of the 2024 workshop was to identify priority data needs that NOAA and other climate service providers could potentially meet. This section highlights some cross-cutting data needs that would support a number of use cases discussed within or across breakouts.

The data needs lie on a spectrum. At one end are the derived and heavily processed quantities that can be used by practicing engineers to implement standards, such as the 1% AEP value of rainfall or AFI. In several instances, there was a request for the underlying data series so that engineers could perform their own analysis. An example that was mentioned would be to serve the series of annual AFI along with the 1% AEP value.

At the other end of the spectrum are the complex data needs of those on standards committees or in research who are using climate model output to estimate future values of engineering parameters. Examples include the need for full atmospheric profiles from multiple GCMs to estimate the frequency of freezing rain for future ice loads, or the plethora of atmospheric variables needed to estimate future thunderstorm winds. This type of data would be delivered to a relatively small number of standards developers or researchers and should be treated separately. The focus below is on data products that would serve the practicing engineer.

4.8.1. Single Variables

Many of the use cases discussed have a primary requirement for a single meteorological variable such as precipitation, temperature or wind. In some use cases auxiliary variables are needed but are handled in terms of “arbitrary point in time” quantities that can be provided separately, and without detailed multivariate analysis.

Rainfall rate, sub-daily: It is not surprising that Intensity-Duration-Frequency (IDF) curves for heavy rainfall stands out as a high priority for engineering applications. 15-minute rainfall rate is viewed as a good “default” that will address the needs of ASCE 7 (roof loads) and ASCE 24. IDF curves at multiple durations, including 15-minute, are planned for NOAA Atlas 15 for both historical observations (Volume 1) and projections (Volume 2). Other potential use cases that would be served by this product include estimating landslide hazard, improved calculation of rain-on-snow loads, input for hydraulic modeling for flooding and inundation, and several compound flooding types. Hourly precipitation rate was also mentioned in hydraulic modeling. The five-minute rainfall rate was seen as useful for urban flooding (ASCE 45, 46, 47, MOP 77, and others). Watershed scale estimates were also discussed in addition to point estimates which would take into account the changing spatial scale of storms.

Precipitation, monthly and seasonal: Annual series and extremes were seen as useful for understating groundwater changes, estimating landslide hazard. Knowing the fraction as rain versus snow was also requested.

Precipitation, Snow: Annual maximum Snow Water Equivalent (SWE) is used by ASCE 7. To calculate reliability-based design snow loads for multiple return periods are needed. Providing annual series of maximum SWE would facilitate this. Having observed and projected daily SWE to calculate duration of snow loads would assist with combined loads and with certain roof loads. Other uses of SWE and snow cover are in permafrost degradation and snow-melt-driven compound flooding. Validation of gridded snow products was seen as essential.

Air Temperature, average daily: Air Freezing Index and Air Thawing Index (annual values and extreme statistics) derived from daily temperature, along with mean seasonal temperature serve many uses in cold regions engineering. This is already a high priority identified in the 2022 workshops. The 2024 workshop revealed many additional uses, particularly for use cases beyond ASCE 32, including for underground utilities and infrastructure.

Temperature daily minimum and maximum: Both the range of daily extremes (i.e., the coldest and warmest temperatures a site is likely to experience in its service life) and the number of freeze-thaw cycles were mentioned in the discussions of the choice, performance, and degradation of construction materials. This is simple to compute and is included here as a potential priority.

Wind Speed: ASCE 7 uses extremes of 3-second wind gust. ASCE MOP 74 (structural loads on Transmission Lines) references ASCE 7 wind gust data. Other durations of gusts (30-second) were mentioned, particularly for Pier and Wharf design using UFC 4-152-01. As gusts are often estimated using scaling relationships, the wider applicability of ASCE 7 wind speeds could be investigated.

Groundwater Elevation: Changes in the water table and other characteristics of ground water due to sea level rise (coastal) and changes in ground water recharge and extraction, would support many use cases identified in the Earth Materials breakout. In addition, several applications related to flooding were discussed.

4.8.1. Multiple Variables

Several use cases involve the need for multivariate datasets. This is particularly true for combined hazards, or where the surface energy and water balance is needed.

Consistent Tidal, Surge, and Wave Data: Having access to combined still water level and wave projections was mentioned, particularly at sites between tide gauges.

River stage and flow, and heavy precipitation coordinated with other coastal flooding mechanisms: Having consistent river stage and flow data at and between/downstream of gauges, coordinated with tide and surge data so that joint probabilities can be estimated. Full series of data may be needed for reliability analyses.

Hydraulic modeling inputs: MOPs specify the use of hydraulic modeling to estimate inundation. Providing suites of variables needed as inputs for common configurations of HEC-River Analysis System model (RAS) and Storm Water Management Model (SWMM) and other commonly used models would serve a number of use cases regarding flooding.

5. Procedural and Process Needs and Priorities

The summary that follows reflects the contributions, expertise, and viewpoints of the workshop participants expressed during the breakout sessions as synthesized by the authors of this report.

Understanding the technical needs of civil engineers as well as the processes that may determine Federal efforts to address these needs (discussed in Sections 1 through 4) are key components of any effort to improve the resilience of the Nation's infrastructure. This section explores procedures and process approaches to turn that understanding into action discussed in three breakout sessions and the associated plenary. Key points raised during the workshop are summarized in the textbox below.

Key Points in Section 5:

The process-oriented breakout sessions were asked to address the following: investigate process flexibility, identify major alignment opportunities, explore effective communication pathways, and determine key next steps. Four high-level areas were identified:

- Identify interim products, mechanisms, and steps to support the practicing civil engineer
- Focus on education
- The need for implementation planning
- Develop the return on investment (ROI) and other economic and societal measures

5.1. Increasing the Pace

Updating and incorporating a standard into building codes can take ten years, during which time an estimated $15 to $18 trillion of new construction will be built (see Section 1). The efforts of the ASCE-NOAA Task Force to date have focused on technical challenges and opportunities for improving the treatment of non-stationarity in weather and climate statistics in future standards and MOPs. The process breakout participants emphasized the need to provide guidance for civil projects being built now in order to minimize the risks due to these projects underperforming or failing early due to changing conditions.

The suggestions from the breakouts were characterized into four themes: 1) identifying interim products, mechanisms, and steps that the breakout participants could take to support the practicing civil engineer; 2) focusing on undergraduate and continuing education's role in advancing engineering practice; 3) recognizing the need for implementation planning, within both ASCE and Federal agencies; and 4) gaining a better understanding of the economics of resilience, as measured by multiple metrics including ROI.

5.1.1. Interim Products, Mechanisms, and Steps

One question raised during the breakout discussions was how to develop pre-standard guidance, test it with the relevant engineering communities of practice for their feedback, and identify possibilities for early implementation. The workshop participants acknowledged to accomplish this would require financial and human resources along with engaging the right people. The importance of effectively getting feedback on early products was stressed. Suggested pre-standard products included guideline documents, technical basis documents (as are developed by the American Society of Mechanical Engineers), MOPs (which can be used upon publication), and other documents that are "more than a journal article" but "less than a standard."

Getting updated and projected climate datasets into the ASCE Hazard Tool was suggested as a near-term action. Using the ASCE Hazard Tool for this purpose will present this data to engineers in a familiar context as well as provide access to a large audience of potential users. The highest priority expressed was for access to NOAA Atlas 15 data when published. Data to support the ASCE 7-28 future conditions chapter is a potential future addition. The desire for additional climate projection data to support a broader engineering practice was also expressed.

The importance of ramping up support for research to enable the creation of relevant products was mentioned. Several such research and product needs were discussed in this workshop. In addition to applied research and product development, fundamental research was desired to increase confidence in characterizing future conditions across hazards.

5.1.2. Education

A clear need was identified for education on what to expect as the process of incorporating future climate conditions into engineering practice unfolds. Education on the importance and urgency of these issues in addition to technical matters was seen as a way to engage the broader engineering community in this process. Communicating the business case for rapid adoption of new standards climate-informed practices (see subsection 5.1.4) was also seen as a potential way to engage. Training the next generation of engineers was also seen as critical. The role of ASCE in engineering curriculum development is a potential leverage point. There was also mention of convincing state licensing boards of the need for this curriculum in their requirements.

The publication of NOAA Atlas 15 and the development of ASCE 7-28 were mentioned as two imminent opportunities to engage with practicing engineers on the technical level. Atlas 14 is likely the NOAA product that civil engineers are most familiar with. The switch from NOAA Atlas 14 to Atlas 15 will no doubt provoke many questions among practicing engineers. What were the deficiencies in Atlas 14? What is the difference between Atlas 15 Volumes 1 and 2? These were just two of many proposed topics that could be addressed through continuing education. Continued conversations with key Federal partners, such as NOAA's Office of Water Prediction (OWP) as the developers of Atlas 15, could help identify opportunities to partner in these education efforts.

Education also could be directed towards demonstrating the need for the move from historical observations to predictive modeling and the implications of such a move. Participants across the breakout groups cited education on the future conditions chapter in ASCE 7-28 as a way to inform engineers of the need and methods for implementing climate non-stationarity in their practice. The ASCE 7-28 committee has become a center of expertise on these topics, and this expertise should be shared more widely within and outside ASCE. Participants also expressed a desire for education on additional topics: gaining a better understanding of climate uncertainty, methods to incorporate non-stationarity into engineering design, and how to better understand and use climate projections (such as the GWL approach presented in Section 3.3).

It was noted that efforts to educate practicing engineers are likely to be more efficient if delivered through existing channels, such as regular webinar series, continuing education courses, the ASCE Seminar Week, and others. ASCE could potentially benefit by partnering in some of these educational efforts with NOAA (the OWP and IPG were mentioned), the National Climate Assessment, and other entities, depending on the topic.

5.1.3. Implementation Planning

It was noted that strategic planning is only as useful as the implementation that follows. Incorporating the development and dissemination of climate-informed engineering standards and practices into implementation planning by ASCE and NOAA (and other Federal agencies) was seen as necessary to ensure success. As a private sector entity that develops and promulgates standards and other guidance, ASCE was seen as the audience for suggestions on this topic from the workshop participants.

Both ASCE and NOAA are large, complex organizations, as are other Federal agencies. There was discussion about how such implementation planning could be incorporated into the ASCE structure. Resources would be needed to be devoted to this, given the volunteer workload of ASCE's members. It was recognized that Federal agencies have different roles and constraints than ASCE or the private sector when it comes to implementation. Developing a clear mutual understanding of the Federal planning and budget process (as was introduced in Section 1) and on how to inform NOAA's planning process was seen as helpful in this regard.

5.1.4. Return on Investment

Gaining a better understanding of the economics of designing and building for climate and infrastructure resilience was seen as both the most important and most ambitious near-term effort. Those involved in developing standards, pre-standards, and other guidance and disseminating their use throughout engineering practice need to think about how to make the business case. It was asked if there are comprehensive studies on the return on investment (ROI) for moving into this climate-informed space. Workshop participants were not aware of any such study or report that would meet their needs on this topic. One possibility raised was the creation of a product similar to the National Hazard Mitigation Saves: 2019 Report (National Institute of Building Sciences, 2019) that focuses explicitly on the ROI of including nonstationary climate hazards in engineering design. The cost of inaction was also mentioned. Comparing ROI over 30 to 100 years, with and without considering the changing drivers of extreme weather and climate events, was suggested as a way to address this. If ASCE and NOAA were to put out such a report, it could have a big impact in the near term. It was emphasized that analysis of costs and benefits should include not only financial ROI but also sustainability ROI, tying in resilience and equity.

A better understanding of ROI could help justify expanded funding for the development of climate-informed engineering standards and their adoption into codes. ROI has both a macro-economic aspect to inform discussions of societal and economic benefits and a micro-economic aspect at the project scale. At the micro-economic level, participants mentioned engagement with FEMA on adding climate information to the benefit cost analysis for FEMA grants. Such efforts would help a variety of decision makers, including financiers, builders, owners/operators, and insurers to understand and better address the economics of extreme weather and climate events reduction at the project scale in a changing climate.

6. Climate Risk Reduction: Opportunities for Joint Action

ASCE recognizes that engineering practices and standards must be revised and enhanced to address climate change and resiliency to reduce vulnerability to failure in functionality, durability, and safety over infrastructure's service lives that are often 50 to over 100 years. Acquiring the weather and climate information needed to inform current and future ASCE engineering guidance requires co-development of key data and data products with relevant scientists. Such co-development, in turn, requires considerable communication and coordination among the potential providers of such information and the ASCE bodies responsible for updating or developing relevant standards and MOPs. Coordinated engagement among such relevant organizations and ASCE entities could build upon past work and extend the value of the ASCE-NOAA Task Force efforts (see textbox for section's key points).

Key Points in Section 6:

The workshop presentations and discussions raised multiple options for the ASCE-NOAA Task Force to improve the ability for the best available science to be integrated into civil engineering standards and MOPs to increase infrastructure resilience.

- Continue to encourage focused discussion and co-development of weather and climate information needed for efficient design and operation.
- Promote cross-engineering discipline dialogue and bring that integrated perspective to discussions with its Federal participants, especially NOAA, as it examines ways to support ASCE's use of climate information in its standards, MOPs, and other products.
- Continue to work across various communities of practice to anticipate areas where relevant engineering guidance is needed or should be updated on a predictable and systematic basis.
- Promote a broader discussion of how data and data products can be presented in an integrated and user-friendly environment, perhaps drawing from various Federal data portals to create a more integrated, one stop shop approach to meet the needs of ASCE members and various committees.

6.1. ASCE Policy Statement and ASCE-NOAA Partnership

ASCE Policy Statement 360 – Climate Change, recognizes the important role civil engineers play in reducing adverse impacts to the built environment caused by extreme weather and climate events (ASCE, 2024). Policy Statement 360 also states clearly that it is the position of ASCE that "Most infrastructure systems typically have long service lives (50 to 100 years) and are expected to remain functional, durable, and safe during that time. These systems are exposed to and are often vulnerable to the effects of extreme climate and weather events. **Engineering practices and standards associated with these systems must be revised and enhanced to address climate change and resiliency to ensure they continue to provide low risks of failures and to reduce vulnerability to failures in functionality, durability, and safety over their service lives**. (emphasis added)."

The ASCE-NOAA partnership, as formalized by the ASCE-NOAA MOU discussed in multiple sections of this report, reflects ASCE's need for transparent and authoritative information about the climate system and the implications for understanding the environmental conditions that buildings and other infrastructure components may experience during their service lives (e.g., 30 to 100 years). A recent study conducted by the National Institute of Building Sciences (National Institute of Building Sciences, 2019), estimated that the adoption of up-to-date hazard-based building codes can yield significant reductions in the cost of extreme weather and climate events. The study estimates that benefit-cost ratios of 11:1 ($11 of loss reduction per $1 spent) can be achieved depending on the peril and geographic setting (Figure 6-1).

	Adopt 2015 Model Codes	Exceeding 2015 Model Codes
Riverine Flood	6:1	5:1
Wind	10:1	5:1
Earthquake	12:1	4:1
Wildland-Urban Interface Fire	N/A	4:1
Overall Benefit-Cost Ratio	**11:1**	**4:1**

Figure 6.1 Benefit Cost Ratios from Adopting or Exceeding Building Codes for Major Types of Perils. The figure shows the analysis of "model" codes referring to those adopted in 2015 by the IBC that represent the minimum requirements while not accounting for any differences in local enforcement of compliance to these codes. Further, IBC already has another round of codes since 2015 (Modified from National Institute of Building Sciences, 2019).

Taken collectively, the above data serves to highlight the need for the authoring committees of various ASCE engineering guidance documents, including both standards and MOPs, to have access to timely, authoritative, and transparent quantitative information regarding likely changes in weather and climate means and extremes. As discussed throughout the workshop and this report, acquiring the weather and climate information needed to inform current and future ASCE engineering guidance requires co-development of key data and data products. Such co-development, in turn, requires considerable communication and coordination among the potential providers of such information and the ASCE bodies responsible for updating or developing relevant standards and MOPs.

6.2. Principles of Engagement Between ASCE and Its Federal Partners

Federal investment in climate modelling, while substantial, has largely been focused on (1) understanding the implications of GHG emissions and mitigation strategies for reducing the rate of global temperature rise and associated changes in key components of the Earth system, and (2) agency specific decisions to mission priorities (e.g., protect public resources including Federally owned infrastructure, critical habitat, or endangered species.) As a consequence, recent efforts to provide relevant information about future weather and climate conditions for specific non-federal user groups are still in development, creating an opportunity for end users like ASCE to play an important role in that development.

6.2.1. Transparency and Co-Development

The widespread use of civil engineering guidance documents such as ASCE standards and MOPs reflect the practicalities of civil engineering practice. Meeting the standard of care expected of professional civil engineers drives an overarching need for consensus guidance so that work can be completed efficiently while maintaining high quality. Thus, ASCE standards and MOPs provide essential information created through complex and rigorous peer review. Discussions during the meeting suggest that data sets and products (such as climate projections) that are used in the development or application of such guidance documents should meet similar standards of peer-review and data quality, and the underlying assumptions or calculations used in their development should be available for scrutiny. Post development review, while essential, is not sufficient to ensure that products, upon completion, are readily usable for civil engineering practice. Co-development of such data sets and products raises the awareness of the end user community and significantly increases the likelihood that the final product will be used effectively. Continued dialogue between civil engineers and producers of weather and climate information is essential to the appropriate incorporation of statistical information about conditions under which infrastructure is expected to function. **The ASCE-NOAA Task Force should continue to encourage focused discussion and co-development of weather and climate information needed for efficient design and operation.**

6.2.2. Greater Specificity, Reliability and Economic Efficiency

Given the complex nature of the weather and climate system and the wide diversity of civil engineering practice that may be affected by changes in that system, a seamless process where product development is tied to any specific engineering decision seems impractical. As discussed in Section 3, the development cycle of major climate model output updates is deeply tied to efforts to support the work of the IPCC. Furthermore, the schedule for updating and re-affirming key ASCE standards across various areas of civil engineering practice is not synchronized so synchronizing the timing of release of weather and climate products to a specific standard would need to be carefully considered. Given the breadth of hazards covered by ASCE 7, as well as its wide adoption in building codes make it one obvious choice as a potential pace setter of the rate of information development and release. Products for ASCE 7 would cover many key environmental hazards and weather and climate processes such as rainfall; snow and other forms of frozen precipitation; straight-line winds and tornadoes; and sea-level rise.

For weather and climate information to be widely utilized, it must be credible and available. The development and use of many ASCE standards and MOPs is predicated on the information being available for the foreseeable future and updated as needed. In other words, access to the data and data products must be reliable and disseminated.

Review of the key weather and climate products discussed in Section 4 however demonstrates that the ASCE-NOAA Task Force needs to avoid becoming overly focused on just one or two standards, even standards as influential as ASCE 7, as the implications of non-stationarity in the statistics of weather and climate has implications for engineering practice outside of structural engineering. Thus, the co-development of civil engineering relevant data and data products will require ASCE and other end user groups to develop more systematic approaches to develop and prioritize their need for, and disseminate, essential environmental data. Discussions at the workshop demonstrate that assembling engineering experts across multiple communities of practice can provide unique insights into such needs and their priority. **The ASCE-NOAA Task Force should promote such cross-engineering discipline dialogue and bring that integrated perspective to discussions with its Federal participants, especially NOAA, as it examines ways to support ASCE's use of climate information in its standards, MOPs, and other products.** The resulting dialogue will be essential in ensuring key information is fit to purpose, accessible, and disseminated. Examining the economics of climate adaptation and mitigation from ASCE perspectives is necessary and worthy of focused pursuits in the future.

6.2.3. Ability to Anticipate Need

With continued encouragement from the ASCE Board of Direction and as stated in ASCE Policy 360, ASCE is exploring mechanisms to provide engineering guidance related to changes in weather and climate through more efficient, timely, and systematic development and updating of ASCE standards and MOPs. To this end, ASCE has created the ASCE Standards Department, which will work across the various institutes and technical committees to provide more uniform support and guidance to various authoring committees. As discussed in plenary session, it is important that such efforts allow ASCE to more fully account for the needs of engineering practice in order to provide a more systematic and comprehensive statement of need relevant to weather and climate information as well as related data and data products to its various Federal partners, especially NOAA. **The ASCE-NOAA Task Force should continue to work across various communities of practice to anticipate areas where relevant engineering guidance is needed or should be updated on a predictable and systematic basis.**

6.2.4. Wider Integration of Federal Efforts

As discussed in Sections 3, 4, and 5, the need for information relevant to changes in precipitation, temperature, winds and windstorms (including tornadoes), and sea level rise is well established. Additional discussions around compound events and changes in the behavior of earth materials related to changes in temperature (e.g., permafrost loss), precipitation (e.g., mass soil movement), and surface and groundwater levels (e.g., compound flooding) suggest that multiple Federal programs can provide relevant data and data products of value to ASCE, its authoring committees, and practicing engineers. **Coordinated engagement among such relevant efforts and ASCE entities could build upon past work and extend the value of the ASCE-NOAA Task Force efforts.** For example, the ASCE-NOAA Task Force could explore mechanisms for including weather and climate information to the benefit cost analysis for FEMA grants.

6.2.5. A Focus on Dissemination and Use

Plenary discussions built on various breakout group discussions to suggest that in addition to weather and climate data being fit to purpose and credible, it would be of most benefit if it were provided in an easily accessible and sustainable manner. **The ASCE-NOAA Task Force should promote a broader discussion of how these data and data products can be presented in an integrated and user-friendly environment, perhaps drawing from various Federal data portals to create a more integrated, one stop shop approach to meet the needs of ASCE members and various committees.** At present, the ASCE Hazards Tool provides support for a limited number of hazard-based codes and standards (e.g., ASCE 7). The potential exists for expanding ASCE Hazards Tool as the basis for such an integrated and civil engineering focused point of access.

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Appendix A. List of Workshop Participants

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Dan Walker	University of Maryland/EA Engineering, Science, and Technology, Inc.
Dan Wunder	NOAA contractor
Dave Rosa	FEMA
David Benson	NOAA
Deke Arndt	NOAA/NCEI
Dennis Lambert	State of Louisiana
Derrick Dasenbrock	Department of Transportation
Don Scott	Donald Scott Consulting

Name	Affiliation
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Eric Tichansky	USACE
Erika Haldi	ASCE staff
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Frank Lombardo	University of Illinois Urbana-Champaign
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Gillian Millar	GHD
Glenn Moglen	University of North Carolina at Charlotte
Grace Yan	Missouri S&T
Greg Soules	CB&I
Guirong (Grace) Yan	Missouri S&T
Heather Brooks	BGC Engineering
Heidi Stiller	NOAA
Jainey Bavishi	NOAA
Jamie Carter	NOAA
Janel Hanrahan	NOAA
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Jayantha Obeysekera	Florida International University
Jennifer Goupil	ASCE staff
Jennifer Jacyna	ASCE staff
Jessica Mandrick	Gilsanz Murray Steficek
Joe Barsugli	NOAA/PSL
Joe Pica	NOAA
Joe Thompson	Government Accountability Office
John Allen	Central Michigan University
John Ingargiola	FEMA
Jonathan Westcott	FEMA
Kelcy Adamec	HDR Engineering
Kelly Mahoney	NOAA
Kimberly Martin	Keller North America
Lauren Mudd	Applied Research Associates
Li Erikson	USGS
Long Phan	NIST
Maggie Coates	NOAA contractor
Marc Levitan	NIST
Mari Tye	University Corporation for Atmospheric Research
Matthew Roberts	ASCE staff
Meghan Edwards	NOAA contractor

Name	Affiliation
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Meredith Carr	USACE
Michael St. Laurent	NOAA
Michelle (Shelby) Bensi	University of Maryland
Mike Langston	USGS
Ming Liu	U.S. Navy
Mitch Heineman	CDM Smith
Morgan Stahl	NOAA contractor
Nathan Chan	University of Maryland
Noah Benitez-Nelson	NOAA contractor
Norma Jean Mattei	University of New Orleans
Oceana Francis	University of Hawaii
Omar Jaradat	Moffat and Nichol
Patrick Barnard	USGS
Peter Vickery	Peter Vickery Consulting
Rachel McCrary	University Corporation for Atmospheric Research
Raed ELFarhan	Weston & Sampson
Regan Murray	EPA
Robert Traver	Villanova University
Rolf Olsen	IE University
Rune Iversen	Simpson Gumpertz & Heger
Russell (Russ) Vose	NOAA
Sanaz Rezaeian	USGS
Shanna Combley	National Aeronautics and Space Administration
Shirley Clark	Penn State Harrisburg
Sihan Li	Rowan Williams Davies & Irwin Inc. (RWDI)
Sissy Nikolaou	NIST
Steve Tebbe	Former NOAA contractor
Teng Wu	University of Buffalo
Teresa Metcalfe	ASCE
Therese (Terri) McAllister	NIST
Tom Knutson	NOAA
William Katzenmeyer, PE	C.H. Fenstermaker Associates, Inc.
William Sweet	NOAA
Yating Zhang	University of Maryland
Yong Wei	NOAA
Zack Labe	NOAA

Appendix B. Workshop Agenda

Note: As of January 2025, the agenda below has hyperlinks to the recording of the plenary sessions.

Climate Risk Reduction ASCE-NOAA Workshop: Hazards and Process

Workshop Chair: Bilal M. Ayyub, PhD, PE, Dist.M.ASCE

MEETING INFORMATION	
Dates	June 25 and 26, 2024
In-person	ASCE Headquarters: 1801 Alexander Bell Drive Reston, VA 20191

Day 1 - Climate-Risk Reduction in Building Practices: June 25, 2024		
Time	**Title**	**Speaker(s) or Leader**
8:30 AM	Networking and Sign-in	Not Applicable
9:00 AM	Opening Remarks	Marsia Geldert-Murphey (ASCE President) and Jainey Bavishi (Assistant Secretary of Commerce for Oceans and Atmosphere and Deputy NOAA Administrator)
9:15 AM	Workshop Goals Building on ASCE-NOAA Task Force Efforts	Ben DeAngelo and Dan Walker (ASCE-NOAA Task Force Co-chairs)
9:35 AM	Federal Budget and Program Cycles Orientation	Caroline Sevier (ASCE Government Relations) and Joe Pica (NOAA)
9:50 AM	ASCE Standards and Building Codes Cycles Orientation	Jennifer Goupil (Managing Director of SEI and ASCE Chief Resilience Officer)

Day 1 - Climate-Risk Reduction in Building Practices: June 25, 2024		
Time	**Title**	**Speaker(s) or Leader**
10:15 AM	Break	
10:30 AM	Panel: ASCE Institutes' Perspectives on Climate Hazards	Institute Representatives: Shirley Clark (EWRI), Don Scot (SEI), Norma Jean Mattei (COPRI), and Sissy Nikolaou (G-I)
11:30 AM	NOAA's Industry Proving Ground - Opportunity for Co-Development of Climate Science Data for Engineering	Russ Vose (NOAA's Industry Proving Ground)
12:15 PM	Break	
12:45 PM	Lunch and Learn: Are Global Warming Levels the Solution to Climate Uncertainty?	Joe Barsugli (University of Colorado/NOAA PSL)
1:30 PM	Breakout Sessions 1 with Technical Focus Based on Priority Climate Data Needs	3 parallel hazard focus sessions (see below): Rainfall, Temperature extremes, and Winds
3:15 PM	Break	
3:30 PM	Breakout Sessions 2 with Technical Focus Based on Priority Climate Data Needs	3 parallel hazard focus sessions (see below): Compound flooding, Snow loads, and Earth materials
5:00 PM	Closing Remarks	Bilal Ayyub (ASCE)
5:30 PM	Day 1 Ends	

Hazards Breakouts

1. Breakout Session 1:
   1.1. Rainfall extremes (e.g., IDF) intensity, duration, and frequency especially with respect to stormwater and flood design
   1.2. Temperature extremes, including with respect to cold regions
   1.3. Wind and related design responses

2. Breakout Session 2:
   2.1. Compound flooding, including compound inland and coastal flooding
   2.2. Snow loads, including rain-on-snow loads
   2.3. Earth material response to changing conditions

Day 2 - Climate Risk Reduction ASCE-NOAA Workshop - Process: June 26, 2024		
Time	**Title**	**Speaker(s) or Leader**
8:30 AM	Networking and Sign-in	N/A
9:00 AM	Summarizing First Day and Orientation to Today's Goals	Dan Walker (ASCE)
9:30AM	Panel: Programmatic Approaches for Durable Federal Agency and ASCE Coordination to Support Engineering Guidance Development	Jennifer Goupil (chair) with Sanaz Riezian (USGS), Terri McAllister (NIST), John Ingargiola (FEMA), and Yong Wei (NOAA/Pacific Marine Environmental Laboratory/CICOES[7])
11:00 AM	Facilitated Plenary Discussion on Principles of Engagement between ASCE and Their Federal Partners[8]	Bilal Ayyub, Ben DeAngelo, and Dan Walker (ASCE-NOAA Task Force Co-chairs)
11:30 AM	Lunch	
12:30 PM	Procedural Breakout Orientation	
1:00 PM	Procedural Breakout	See below
2:15 PM	Break	
2:30 PM	Reporting from Day 2 Breakout Sessions	Breakout Facilitators
3:00 PM	Panel: Next Steps for Operationalizing of Climate Data into ASCE Codes and MOPs[9]	Bilal Ayyub, Ben DeAngelo, and Dan Walker (ASCE-NOAA Task Force Co-chairs)

[7] Cooperative Institute for Climate, Ocean, & Ecosystem Studies
[8] The above recording has the plenary and this session.
[9] Due to weather conditions at the workshop, the last sessions were compressed to allow people to travel.

3:30 PM	Closing Remarks	Bilal Ayyub (ASCE)
3:45 PM	Day 2 Ends	

Procedural Focus Breakouts:

- Each breakout team should identify two to three major goals through 2027. Each group provides milestones for next year to progress toward establishing the supportive procedures for operationalizing the uptake of the best available science data into ASCE codes and standards such that the feedback of one system informs the other.

Appendix C. Acronyms and Abbreviations

3°C	three degree Celsius
ACI	American Concrete Institute
AEP	Annual Exceedance Probability
AFI	Air Freezing Index
ANSI	American National Standards Institute
APT	Arbitrary Point in Time
ASCE	American Society of Civil Engineers
ASCE-NOAA Task Force	ASCE-NOAA Task Force for Climate Resilience in Engineering Practice
Atlas 14	Precipitation Frequency Atlas of the United States
ASTM	American Society for Testing and Materials
ATI	Air Thawing Index
BCA	Benefit Cost Analysis
BLM	Bureau of Land Management
BSSC	Building Seismic Safety Council
CAPE	Convective Available Potential Energy
CIN	Convective Inhibition
CMIP	Coupled Model Intercomparison Project
COPRI	Coasts, Oceans, Ports, and Rivers Institute
CORA	NOAA's Coastal Reanalysis
CPO	Climate Program Office
CTSM	Center for Technology and Systems Management
DIGGS	Data Interchange for Geotechnical and Geoenvironmental Specialists
DOC	Department of Commerce
EHP	Earthquake Hazards Program
EPA	Environmental Protection Agency
EWRI	Environment and Water Resources Institute of ASCE
FEMA	Federal Emergency Management Agency
FFRD	Future Flood Risk Data
FIRO	Forecast Informed Reservoir Operations
FY	Fiscal Year
G-I	Geo-Institute
GCM	Global Climate Models
GHG	Greenhouse Gas
GWL	Global Warming Level
IBC	International Building Code
IDF	Intensity-Duration-Frequency
IPG	Industry Proving Grounds
IRA	Inflation Reduction Act
km	Kilometer

LCSC	Load Combinations Sub-Committee
MRMS	Multi-Radar, Multi Sensor
MOP	Manual of Practice
MOU	Memorandum of Understanding
NCEI	National Centers for Environmental Information of NOAA
NEHRP	National Earthquake Hazards Reduction Program
NFIP	National Flood Insurance Program
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NSHM	National Seismic Hazard Model
NTHMP	National Tsunami Hazard Mitigation Project
OWP	Office of Water Prediction
PMEL	Pacific Marine Environmental Laboratory
PMP	Probable Maximum Precipitation
PSL	Physical Sciences Laboratory (NOAA)
PUC	Provisions Update Committee
RAS	River Analysis System
RCM	Regional Climate Model
RC	Risk Category
RH	Relative Humidity
R&D	Research and Development
ROI	Return on Investment
ROS	Rain on Snow
Sec.	Section
SEI	Structural Engineering Institute
SLR	Sea Level Rise
SNOTEL	SNOpack TELemetry
SST	Sea Surface Temperature
SWE	Snow Water Equivalent
SWMM	Storm Water Management Model
TBD	To Be Determined
TC	Tropical Cyclone or Hurricane
TDZ	Tsunami Design Zone
TKE	Turbulent Kinetic Energy
UMD	University of Maryland, College Park
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
VIC	Variable Infiltration Capacity
WLSC	Wind Load Sub-Committee

Appendix D. Detailed Rubric for Hazard Breakout Tables

The workshop organizers recognized that there are many definitions of “hazard” and other terms used in the table. The descriptions (below) are to help clarify our intended usage. The definitions are not absolute. Please note that the workshop tables that follow the rubric are summaries of the breakout discussions, and as such, the content is not consistent across them and contain informal language like abbreviations or first person.

Use Case. Engineering application or calculation where the environmental condition is used for the engineering analysis. The use case associated with existing standards may duplicate other columns (e.g., “Wind Load Calculation in ASCE 7”) or may come from other engineering practice (e.g., “Landslide Hazard Analysis”). There may be multiple use cases for a given design value, or multiple design values for a given use case. For this report’s purposes it is better to list separate use cases if they are sufficiently distinct.

(Environmental) Hazard. The type or types of climatological, meteorological, or hydrological condition, generally stated, that is the input to the design or assessment of a failure mode. The engineering design variable is often derived from an extreme value of the environmental hazard. Specific information can be provided in other columns. These entries will help the ASCE-NOAA Task Force map the engineering uses to broad categories of climate data and to the expertise needed to develop products.

Key Design Variable(s) (i.e., Engineering Value). A specific description of the design variable used in the engineering analysis or required by an engineering standard. This is often the result of a calculation using the environmental variables as inputs but may simply be an environmental variable if there is no significant transformation.

Relevant ASCE Standards/MOPs. The standards documents, MOPs, or other references that an engineer would use in performing the engineering analysis. Examples include ASCE 7 Flood Supplement and MOP 77.

Primary/Secondary/Tertiary Weather of Climate Input Value. The weather and climate values that are needed to complete the engineering calculations. Ancillary geophysical datasets such as soil type or digital elevation model may be mentioned in the table in the spatial resolution or comments columns as the breakout participants decided.

Needed spatial resolution. The breakout participants were asked to recognize a needed value that is representative of the project site. For this entry, if possible, consider the level of spatial detail of typical data products that are currently used, or of other datasets such as soils or vegetation that are used so that climate data can be provided on similar scales.

Design or Service Life Length. The data may express multiple time scales for different types of projects under the use case. For example, bridges may have a longer design/service life than other structures.

Necessary Data Characteristics. This column allowed participants to include aspects of the data such as specific statistical treatment, geographical coverage, etc. Accordingly, the contents may repeat information in other columns (e.g., 0.01 AEP or seasonal values).

Comments. This provided the groups with space to add additional points to be noted from the discussions. They will inform the text of the report related to the engineering use case or environmental hazard or capture information for future discussions.

Extreme Temperature, Emphasis on Cold Regions

Breakout	Use Case	Hazard	Key Design Variable (i.e., Engineering Value)	Relevant ASCE Standards/Codes/MOPs	Primary Weather or Climate Input Value	Secondary Weather or Climate Input Value	Tertiary Weather or Climate Input Value	Needed Spatial Scale/Resolution	Design or Service Life Length	Necessary Data Characteristics (e.g., distribution, average, maximum, or minimum)	Comments
Temperature Effects on Sub-surface incl. Soils and Permafrost											
Temperature	piping, pipelines	Depth of permafrost active layer	Air thawing index; Air freezing index	Cold Regions Utilities Manual (Monograph)	Daily Average Temperature	Snow cover	Wind speed	Community scale (25-50 km) [*winters are warming faster and have more impact on design]	25 to 75 years	Daily, seasonal/sub-seasonal. Seasonal differences in warming.	Cold Regions Utilities Monograph (Manual) focuses on the design, construction, and operation of infrastructure components for the delivery of water, the removal of liquid and solid wastes, and the provision of power for services in the extremely cold environments found in the far north or south. warming and the winter actually has more of an impact on design than the warming in the summer
Temperature	water treatment	Depth of permafrost active layer	Air thawing index; Air freezing index	Cold Regions Utilities Manual (Monograph)	Temperature	Humidity				Daily T used for ATI. Seasonal differences in warning	
Temperature	Thermal design in permafrost regions	Depth of permafrost active layer	Air thawing index; Air freezing index	Cold Regions Utilities Manual (Monograph)	Daily Temperature	Snow cover	Wind speed	Community scale (25-50 km) [*winters are warming faster and have more impact on design]	25 to 75 years	Daily, seasonal/sub-seasonal. Seasonal differences in warming	Goal is ofter to keep the ground frozen. All factors that affect surface energy balance are desired. Need for seasonal/monthly values at a minimum.
Temperature	building foundation design-- permafrost	Depth of permafrost active layer	Air thawing index; Air freezing index		Temperature	Snow cover	Rainfall				May need to build deeper as permafrost active layer depth increases.
Temperature	Air Quality (methane intrusion)	Depth of frost penetration and release of methane	Air thawing index; Air freezing index		Temperature	Humidity					
Temperature	Pavement	Frost Heave	Air thawing index; Air freezing index	Frost Action in Soils: Fundamentals and Mitigation in a Changing Climate	Temperature	Snow cover					Frost Action in Soils is a book with three use cases on mitigating damages; warming in the winter actually has more of an impact on our design than the warming in the summer
Temperature	Building foundation design	Thaw weakening	Air thawing index; Air theezing index	Frost Action in Soils: Fundamentals and Mitigation in a Changing Climate	Temperature	Rainfall					
Temperature	Building foundation design--permafrost	Depth of frost penetration	Air freezing index	ASCE 32: Frost-protected Shallow Foundations	Temperature					100-year return (0.01 AEP) of Air Freezing Index. Annual average temperature > 32°F	Noted in 2022 Workshops; NOAA grant in progress to update current AFI product and produce nonstationary and projected values.
Temperature Effects on Exposed Materials and Structures											
Temperature	Construction material expansion, Construction material performance, Building enclosure design	Excessive temperature and temperature range	Maximum air temperature, Maximum material temperature		Temperature (range of temps)	Insolation		Regional	5 (asphalt) 75 - 100 (building enclosure)	Extreme temperature duration (prolonged exposure).Typical temperature at a time period (e.g. temperature when material was installed); extreme high, extreme low.	Construction material expansion (asphalt, steel, concrete), Construction material performance (Sealants, adhesives), Building enclosure design

Breakout	Use Case	Hazard	Key Design Variable (i.e., Engineering Value)	Relevant ASCE Standards/Codes/MOPs	Primary Weather or Climate Input Value	Secondary Weather or Climate Input Value	Tertiary Weather or Climate Input Value	Needed Spatial Scale/Resolution	Design or Service Life Length	Necessary Data Characteristics (e.g., distribution, average, maximum, or minimum)	Comments
Temperature Effects on Exposed Materials and Structures											
Temperature	Construction material degradation (reinforced concrete cracking, steel corrosion)	Excessive relative humidity		American Concrete Institute and ASTM standards	Atmospheric Humidity	Temperature	Rainfall			Trends in means were discussed	
Temperature	Construction material degradation (Concrete deterioration)	Temperature Freeze-Thaw	Number of Freeze-thaw cycles	American Concrete Institute and ASTM standards	Daily min and daily max temperature	Precipitation		Regional changes	50 to 100 years	Historical vs current vs future freeze-thaw cycle on a daily scale (daily min and daily max)	What are the climate data that supports this and specific indices that can be provided? Should ASCE coordinate with ACI and others on this? Engineer/Architect may need to have temperature values for material selection according to standards.
Temperature	Heat exchanger efficiency in nuclear power plants, other "safety-first" applications	Excessive humidity and high temperature	AEP temperature, long-term average temperature, water temperature	ASHRAE					Design life is shorter for mechanical systems (10-20 yr) but high consequences of failure	long-term average temperature, AEP of daily temperature.	High consequence implies considering small AEP (high MRI)
Temperature	Heat exchanger efficiency in data centers	Excessive humidity and high temperature	AEP temperature, long-term average temperature, water temperature	ASHRAE					10-20 yr (mechancal systems) 50-75 (building envelope)		mechanical systems have short lifetime, but this interacts with building envelope design choices which have long service life
Temperature	Building envelope design, facades and roofing	Extreme Temperature	Temperature of material	ASTM, ACI, others who test materials.	air temperature	insolation	wind speed		10 - 20 yr		Engineer/Architect may need to have temperature values for material selection according to standards.
Temperature	Utility lines (above ground and below ground)	Extreme or Prolonged Low Temperature	Air thawing index; AEP minimum temperature		Temperature	Ice	Wind	25 - 50 km			Will relative humidity increase? (potential data need)
Temperature	Transportation Engineering	Extreme high temperature	Extreme Daily Maximum Temperature	ASCE 21-Automated People Movers	Temperature					50-year MRI (2% AEP) value of daily maximum temperature computed according to methods detailed in ASHRAE Handbook	Noted in 2022 Workshops; NOAA grant in progress to update current product and produce nonstationary and projected values.
Water Temperature											
Temperature	multiple (coastal, water treatment, ecological applications)	Water temperature high (ecological, mechanical (thermal transfer), structural, etc.)	Water temperature in oceans, rivers, reservoirs, lakes		Surface air temperature	Water temperature at surface and multiple depths (stratified)		Body of water (coastlines/shorelines/rivers)	75 years	Extrema, annual average (air thawing index); daily/sub-daily (data and product)	lack of water temperature observations in Arctic. Need temperature for oceans rivers lakes, surface and at various depths.
Temperature	multiple (coastal, water treatment, ecological applications)	Water temperature low (icing, frazil icing, ice loading)	Water temperature in oceans, rivers, reservoirs, lakes		Surface air temperature	Water temperature at surface and multiple depths (stratified)	Ice levels and depth	Body of water (coastlines/shorelines/rivers) (Correlate with CRREL on ice jam data)	30 to 75 years	Extrema, annual average (air thawing index); daily/sub-daily (data and product)	cumulative freezing degree days, provide raw data along with product.

Breakout	Use Case	Hazard	Key Design Variable (i.e., Engineering Value)	Relevant ASCE Standards/Codes/MOPs	Primary Weather or Climate Input Value	Secondary Weather or Climate Input Value	Tertiary Weather or Climate Input Value	Needed Spatial Scale/Resolution	Design or Service Life Length	Necessary Data Characteristics (e.g., distribution, average, maximum, or minimum)	Comments
Temperature Contribution to Compound Hazards											
Temperature	Concrete deterioration	Wildfire	Heat [compound w/ fires]		Wildfires	Temperature	Wind	Small scale/regional [Remote regions; regions with high amounts of fuel]	N/A (bridges, foundations, each different and based on single-incident/disasters)	Compatible with Wildfire hazard mapping (including proximity to fuel)	Note wildfire risk increasing even outside of the Western US: examples Quebec, Appalachians, etc.
Temperature	Buildings on sloped surface; Landslide debris hazard for buildings on flat surface	Soil Saturation	Soil moisture	Geotechnical - See Earth Materials Breakout	Precipitation, snow cover	Temperature		Based on soil characteristics Expansive soils tend to be most impacted by moisture. Resolution of soil type aligns w/ spatial resolution of climate data	75 to 100 years	Duration of extrema, mean	Auxiliary Information: Soil Type/properties. Location of expansive soils extent can determine resolution needed

Rainfall Extremes Especially with Respect to Stormwater and Flood Design

Breakout	Hazard Response	Use Case	Key Design Variable (i.e., Engineering Value)	Relevant ASCE Standards/Codes/ MOPs	Primary Weather or Climate Input Value	Secondary Weather or Climate Input Value	Tertiary Weather or Climate Input Value	Needed Spatial Scale/ Resolution	Design or Service Life Length	Necessary Data Characteristics (e.g., distribution, average, maximum, or minimum)	Comments
Building External Loads											
Precipitation	Roof failure due to surcharge of secondary drainage	Building External Loads	Design rain load (ASCE 7$8.2)	ASCE 7	15-minute precipitation rate					X% AEP value(s) or annual maximum series.	Engineering Use Case detail: Accumulation of water on roof if drain system fails. ASCE 7 refers to NOAA ATLAS 14. ATLAS 15 will likely replace this. Confidence level wasn't discussed or requested. Instead seems to be incorporated into the category for design - i.e., lower AEP for a higher risk application (hospital, nuclear facility...)
Precipitation	Fluvial (riverine) flooding	Building External Loads	Hydrostatic load (ASCE7$5.4.2) Hydrodynamic load (ASCE7$5.4.3) refers to ASCE 24	ASCE 7, ASCE 24	FEMA flood depth or hydrograph for in house hydr. model					X% AEP	
Precipitation	Rain-on-snow loading on roof, and inundation	Building External Loads	Rain on snow surcharge load (ASCE7$7.10)	ASCE 7	Currently treated as 8lb/sqft					Changing probability	Load combination case
Precipitation	rain-on-snow inundation	Building External Loads	Hydrodynamic load with reference to risk from ASCE 24	ASCE 7, ASCE 24	FEMA flood depth or hydrograph for in house hydr. model					Changing probability needing update in FEMA flood models?	
Stormwater Control											
Precipitation	Highway/road/street flooding	Urban stormwater systems	Peak rate of discharge (ASCE45$4.1)	ASCE 12; ASCE 33?; ASCE 45, ASCE 68 ASCE MOP 153 CH4;	5 or 15 minute precipitation rates, or design storm of record	soil moisture.			Varies - dependent on authority. Typical 2%AEP highway, 10%AEP local roads	50% AEP minimum	At present use Atlas 14 or storm of record passed through SWMM (e.g. 10 years simulation) to identify 2 year storm probability
Precipitation	Watercourse pollution	Sewerage design/ combined sewer overflows	inflow hydrology, rainfall data and distribution, curve numbers or runoff coefficients, times of concentration or travel time, and unit hydrograph (ASCE 63$8.1)	ASCE 12; ASCE 33?; ASCE 45; ASCE 62 ASCE MOP 150 Ch3	5 or 15 minute precipitation rates	soil moisture.			Varies - dependent on authority. Typical 2%AEP highway, 10%AEP local roads	"The design storm return period is often specified in the local ordinances." ASCE 45-16 $ 4.1.3 "Typical design return periods reported in the literature are • 2-15years,with10 years common for storm sewers in residential areas, • 10-100 years, depending on the economic justification for storm sewers in commercial and high-value districts. The design return periods established in regulatory ordinances should be viewed as minimum design standards. It may be appropriate to select a design standard that exceeds these mini- mums (e.g., for critical community utilities, major highways, and evacuation routes)." 4.1.1	
Hydrologic and Hydraulic Modeling											
Precipitation	Fluvial (Riverine) flooding - leading to structural failure, inundation of streets, buildings, roads.	Hydraulic Modeling such as SWMM, HEC-RAS generating Area of inundation, depth of flooding, volume of flooding. Time of flooding (multiple watersheds)	Peak reduction factor/spatial distribution, areal reduction factor, downstream hydrograph, time of concentration	ASCE 24; ASCE 12 ASCE 33, ASCE 34 ASCE 56, 57, 62	Relative humidity	Temperature	Evapotranspiration, land cover/land use	Using 1km MRMS gridded precipiation data	Varies - dependent on authority. Typical 2%AEP highway, 10%AEP local roads. 1% Floodplain (bridges)	netCDF, *need for standardization across data products*	Hydrologic model used: H&H storm-water model (SWM). Land use and land cover data currently handled by USGS, update recurrence should be more frequent (more than 3-year basis)
Precipitation	Flood - controlled release of water	Reservoir Design and Operations	Watershed-cumulative precipitation IDF curves for hydrologic modelling	ASCE 40? Likely MOPs or governed by USACE/Bureau Reclamation/Bureau Land Management	Design storm events (as defined by local standards)			Watershed-scale, city to parcel scales (e.g., urban flooding/hydrologic modelling). Sub-hourly data required (15-minute).	Seasonal operations	Flood vs drought in Western US, Eastern US more concerned about flood management and water for recreation and ecosystem management	Complementing Atlas14 data to support watershed-scale analysis, moving away from point-based IDF estimates. Note: how should we balance NOAA-provided products with the work of hydrologic modellers in engineering positions? Desire for a *number*. A hyetograph and complimentary hydrograph would be very useful

Breakout	Hazard Response	Use Case	Key Design Variable (i.e., Engineering Value)	Relevant ASCE Standards/Codes/ MOPs	Primary Weather or Climate Input Value	Secondary Weather or Climate Input Value	Tertiary Weather or Climate Input Value	Needed Spatial Scale/ Resolution	Design or Service Life Length	Necessary Data Characteristics (e.g., distribution, average, maximum, or minimum)	Comments
Reservoir Operations in Flood and Drought											
Precipitation	Water supply for resevoir operations/sedimentation at outlet	Reservoir operations	Flow rate	ASCE 40? Governed by USACE, or Bureau of Reclamation	NOAA River Forecast Center (RFC), NRCS seasonal forecasts	Gridded precipitation products provided in near real-time for modelling the affects of extreme events on aquifer modelling		Historical hourly observations combined with near-real time and projected hourly values. Historical cumulative seasonal values	Seasonal operations	Consider the same variables as contribute to curent FIRO (forecast informed reservoir operations)	Economic, industry impacts. Note: rain-on-snow still needed, drought & flooding built-in with accurate water supply modelling Consider the same variables as contribute to curent FIRO (forecast informed reservoir operations)
Precipitation	Drought	Low flow hydrology	Precipitation dearths, low flow hydrology	ASCE 40; MOP70 Ch13	Gridded rainfall information with surface-validated observations	Relative humidity	Evaporation/ET/Soil moisture	Using 1-4km PRISM data	seasonal operations		Currently using "standard NOAA precipitation products", MRSM, ERA5 & PRISM as examples

Snow Loads, including Rain-on-Snow Loads

Breakout	Use Case	Hazard	Key Design Variable (i.e., Engineering Value)	Relevant ASCE Standards/Codes/MOPs	Primary Weather or Climate Input Value	Secondary Weather or Climate Input Value	Tertiary Weather or Climate Input Value	Needed Spatial Scale/Resolution	Design or Service Life Length	Necessary Data Characteristics (e.g., distribution, average, maximum, or minimum)	Comments
ASCE 7 Snow Load											
Snow	ASCE 7-Snow Load--basic	Snow load	Snow load (snow water equivalent) - daily scale	ASCE 7	SWE (maximum annual, whole distribution)			4km or less (or way to downscale for the mountains)	~50 years for buildings	Annual Maxima, whole probability distribution of tails. East of Rockies: regional summaries, west of Rockies: more specific data needed	Target snow load s determined from a probabilistic reliability analysis for a simple steel structure. The values are chosen from an analysis using extreme value theory, but the return level is chosen based on the probability of failure. Therefore, the entire tail of the distribution needs to be characterized. Guidance on what local communities would be helpful, particularly for spatial scale/regionalization of change factors.
Snow	ASCE 7- Snow load -- drifting	Snow drift	peak snow load within drift	ASCE 7	SWE (maximum annual, whole distribution)	Winter wind (percent of hourly winds above 10mph during winter months)		As fine as possible, with consideration for geography and topography	~50 years for buildings		
Snow	ASCE 7 Snow Load in Combined Loads	Snow in combined loads	snow load	ASCE 7 Combined Loads chapter							Combined loads often use "arbitrary point in time" loads to combine with an extreme value of the other load. Statistical treatment of data for APT loads is different than for extremes. future work could include conditional values ("wind when snow is on the ground", for example)
Snow	ASCE 7 Snow Load - Rain on Snow, development of standard	Rain on snow	combined weight from rain and snow	ASCE 7	SWE (maximum annual, whole distribution, as well as daily values)	Sub-Hourly precipitation coincident with daily SWE		As fine as possible, with consideration for geography and topography	~50 years for buildings		ROS combines daily values of snow with hourly rainfall -- because rain moves through the snow on a roof quickly.
ASCE 7 Ice Load											
Snow	ASCE 7 - Ice Load	Freezing rain, and other precip phases	ice thickness (as deposited on structures or transmission lines)		precipitation amount and phase (ice, freezing rain, etc.)	wind	dewpoint temperature, pressure.	not sure how to answer because it varies regionally and those regions could shift	structures (~50) bridges (~75) transmision structures (~100)		Ice deposition on structures is calculated from observations where the precipitaiton type (phase) is known. To work from models, whether weather forecast models or climate models, empirical methods (such as the Bourgouin method) are used to model the precipitation phase based on the temperature and humidity at multiple levels in the atmosphere. It is unclear whether the precipitation phase from model microphysical packages would be useful.
Other Use Cases											
Snow	Cold Regions -- multiple.	permafrost thaw, frost penetration	heat/cold flux into ground		Snow Cover/Depth						See Temperature Breakout
Snow	Water Resources - - multiple	Heavy Snopack Runoff; declining snowpack	SWE	EWRI	SWE			catchment or basin scale			Not discussed in detail. Hydrological analysis and modeling is a large and complex topic which has a considerable literature related to climate change.

Wind and Related Design Responses

Breakout	Use Case	Hazard	Key Design Variable (i.e., Engineering Value)	Relevant ASCE Standards/Codes/MOPs	Primary Weather or Climate Input Value	Secondary Weather or Climate Input Value	Tertiary Weather or Climate Input Value	Needed Spatial Scale/Resolution	Design or Service Life Length	Necessary Data Characteristics (e.g., distribution, average, maximum, or minimum)
ASCE 7 Wind Processes										
Wind	Minimum Design Wind Load Calculation for Buildings and Other Structures	Wind (non-tornado)	**Basic Wind Speed:** 3-second peak gust at 10 m height over open terrain **Hourly Wind Speed:** Hourly averaged wind speed; 10 m height over open terrain	ASCE 7	Wind (mean and gust)	Temperature	Pressure	Ideal: All available levels at highest possible spatial resolution	>=50 yrs	Ideal: Full time series data for U.S. locations
Wind		Wind (tropical)	Basic Wind Speed	ASCE 7	Wind at 850 hpa level, 250 hpa level	surface, tropopause temperature	Pressure at all levels	<10km	>= 50 yrs	storm maximum
Wind		Wind (extratropical)	Basic Wind Speed, Hourly Wind Speed	ASCE 7	Wind speed (east-west & north south) at 10 m height, TKE (Turbulent Kinetic Energy)	CIN, CAPE, 2 m air temperature		<10km	>= 50 yrs	monthly max or annual max
Wind		Wind (thunderstorm)	Basic Wind Speed	ASCE 7	TKE, Wind Shear	CIN, CAPE, 2 m air temperature, Lifted Index, Dewpoint Depression		<10km	>= 50 yrs	storm maximum
Wind		Wind (tornado)	Basic Wind Speed (terrain undefined)	ASCE 7-22	TKE, Wind Shear	CIN, CAPE, 2 m air temperature, Lifted Index, Dewpoint Depression		<10km	>= 50 yrs	storm maximum
ASCE 7 Wind Hazards										
Wind	Naval Facility Design	Wind (storm type undefined - "stationary")	30-sec gust (10 m height and terrain unspecified assumed Exposure D)	USN Unified Facilities Criteria (UFC)	Wind (mean and gust)					
Wind	Transmission Lines	Wind (non-tornado)	Basic Wind Speed (from ASCE 7)	ASCE MOP 74 (Electrical Transmission Line Structural Loading)	Wind gust				1/100 AEP (100 year MRI)	
Wind	Wind and Wave Analysis/Modeling	Wind (extratropical and tropical)	N/A	N/A						
Wind	Damage and Risk Modeling	Wind (all types)	N/A	N/A						
Wind	Building Facade Performance	Wind (all types)	Duration of wind speed above some threshold	N/A						

Changes in Earth Materials Behavior, Related to Temperature and Precipitation

Breakout	Use Case	Hazard	Key Design Variable (i.e., Engineering Value)	Relevant ASCE Standards/Codes/MOPs	Primary Weather or Climate Input Value	Secondary Weather or Climate Input Value	Tertiary Input Value (may or may not be climate variable)	Needed Spatial Scale/Resolution	Design or Service Life Length	Necessary Data Characteristics (e.g., distribution, average, maximum, or minimum)	Notes for Report Narrative
Groundwater Effects on Structural Loads											
Earth materials	Lateral groundwater loading	Changing groundwater elevation	Groundwater elevation (this is currently only taken once at the beginning of the project) Phreatic water level	ASCE 7	Seasonal precipitation	Sea level rise (for coastal settings)	Land use/land cover change; surface aquifer (groundwater table) extent and recharge/discharge locations	Watershed scale Localized coastal sea level rise map	50 to 100 years	We would do the measurements for the current situation to understand the correlations between the groundwater recharge and the precipitation that happens out on site, and then we would use climate projected precipitation data to understand how the groundwater might change.	A primary concern is implication for wall design (SLR is an additional concern for sea walls). We design for a specific elevation with our drainage like behind the wall drainage system, but that drainage system needs to be designed to make sure that we deal with the amount of water arriving at the wall.
Earth materials	Uplift or buoyancy loading	Changing groundwater elevation	Groundwater elevation (this is currently only taken once at the beginning of the project) Phreatic water level	ASCE 7	Seasonal precipitation	Sea level rise (for coastal settings)	Land use/land cover change; surface aquifer (groundwater table) extent and recharge/discharge locations	Watershed scale Localized coastal sea level rise map	50 to 100 years	For critical structures, we would do the measurements for the current situation to understand the correlations between the groundwater recharge and the precipitation that happens out on site, and then we would use climate projected precipitation data to understand how the groundwater might change.	A primary concern is implication for structures with basements (SLR is an additional concern in coastal areas). Applicable for any buried water free structure. We design for a specific elevation with our drainage like behind the wall drainage system, but that drainage system needs to be designed to make sure that we deal with the amount of water arriving at the wall.
Earth materials	Soil Liquefaction	Changing groundwater elevation	Groundwater elevation (this is currently only taken once at the beginning of the project) Phreatic water level (note: can climate change affect the soil depth enough to have an impact)	ASCE 7 (Seismic)	Seasonal precipitation	Sea level rise	Soil moisture. soil type, geologic setting (historical precedents)	Watershed scale Localized coastal sea level rise map	50 to 100 years	For critical structures, we would do the measurements for the current situation to understand the correlations between the groundwater recharge and the precipitation that happens out on site, and then we would use climate projected precipitation data to understand how the groundwater might change.	Either going to be a concurrent hazard with seismic activity or it's going to be a concurrent hazard with some type of construction activity. Typically thought of as risk increase or development in areas adjacent to known risk
Mass Movement of Rock and Soils											
Earth materials	Mass movements of soils (excluding active layer detachments and retrogressive thaw slumps)	Changing groundwater elevation	Pore water pressure change [Note: Faulted areas Vegetation change: long term (drought) or short term (wildfire) Major precip event]	Geo-Institute, ASCE 7 (for global stability)	Seasonal to interannual precipitation		Vegetation change: long term (drought) or short term (wildfire). NOTE: Stream avulsion and other external factors related to precipitation change can play a factor at the project scale)	Watershed to project scale	50 to 100 years	Magnitude and duration of precip events	Note: mass movement of soils to encompass many types of movements including earth slide, earth flow, debris slides, debris flows and debris floods. But like the AASHTO Standard, the FHWA a design standards all include Those minimum values that these products would need to feed into. Excluded mass movement types for permafrost environments are discussed in the Temperature section. Natural hazards generally we accept that we cannot change, alter or stop the movement so no design life is considered. For analysis of global stability of built infrastructure, the design life of these analyses matches the life of the structure.

Breakout	Use Case	Hazard	Key Design Variable (i.e., Engineering Value)	Relevant ASCE Standards/Codes/MOPs	Primary Weather or Climate Input Value	Secondary Weather or Climate Input Value	Tertiary Input Value (may or may not be climate variable)	Needed Spatial Scale/Resolution	Design or Service Life Length	Necessary Data Characteristics (e.g., distribution, average, maximum, or minimum)	Notes for Report Narrative
Mass Movement of Rock and Soils											
Earth materials	Mass Movement of Rock	increased freeze thaw cycles	Freeze-thaw cycles	Geo-Institute	Daily min and max temp	solar radiation		project scale	50 to 100 years	Number of cycles of freeze and thaw, solar radiation	Note: Mass movements of rock encompass many types of failures and failure modes. For natural hazards generally geotechnical engineers accept that there is no possibility that we can alter or stop the movement, so no design life is considered. For analysis of global stability of built infrastructure, the probabilities and magnitudes of events are considered.
Earth materials	Mass Movement of Rock	Changing groundwater elevation	Pore water pressure change [Note: Faulted areas Vegetation change: long term (drought) or short term (wildfire) Major precip event]	Geo-Institute, ASCE 7 (for global stability)	Seasonal to interannual precipitation		Vegetation change: long term (drought) or short term (wildfire). NOTE: Stream avulsion and other external factors related to precipitation change can play a factor at the project scale)	Watershed to project scale	50 to 100 years	Magnitude and duration of precip events	Note: Mass movements of rock encompass many types of failures and failure modes. For natural hazards generally geotechnical engineers accept that there is no possibility that we can alter or stop the movement, so no design life is considered. For analysis of global stability of built infrastructure, the probabilities and magnitudes of events are considered.
Frost Heave, Permafrost Degradationa and Subsidence											
Earth materials	Frost Heave	Changing groundwater elevation	Air freezing index and groundwater elevation	ASCE 32	Daily air temperature	Seasonal to interannual precipitation	Vegetation change: long term (drought) or short term (wildfire). NOTE: Stream avulsion and other external factors related to precipitation change can play a factor at the project scale)	Watershed to project scale	10 (roads) 50 years (foundations)		Usually design air freezing index is typically used for these calculations.
Earth materials	Frost Heave	Increasing Air Freezing index	Air freezing index and groundwater elevation	ASCE 32	Daily Air temperature	Seasonal to interannual precipitation	Soil moisture. soil type	regional to project scale	10 (roads) 50 years (foundations)	Extrema in air freezing index (design freezing index = average of 3 coldest winters in the last 30 years)	Usually design air freezing index is typically used for these calculations.
Earth materials	Permafrost Degradation	Increasing air temperatures	Air thawing index/air freezing index	N/A	Daily air temperature	Precipitation (in total and as snow)	Wind speed at 3 m and wind direction (passive cooling from either wind speed or having enough cold in the winter to initiate natural convection)	Community to regional	20 (roads) 50 to 75 years (foundations)	Average annual air thawing idex, Design air thawing index (3 warmest summersin the previous 30 years)	Projected air thawing and air freezing index are used to create a sinusoidal model for equivalent temperature climate boundary conditions in thermal modelling. This process is used for both historical and projected air freezing and thawing indices.
Earth materials	Permafrost Degradation	changing water flow patterns	Precipitation	N/A	Preciptiation (in total and as snow)	Daily Air Temperatures	Wind speed at 3 m and wind direction (passive cooling from either wind speed or having enough cold in the winter to initiate natural convection)	Community to regional	20 (roads) 50 to 75 years (foundations)	annual and monthly total precipitation	Increased conductive heat transfer can rapidly alter the presence of permafrost
Earth materials	Subsidence due to aquifer drawdown	Changing Groundwater elevation	Increasign effective stress	Geo-Institute, EWRI, UESI	Seasonal to interannual precipitation		Vegetation change: long term (drought) or short term (wildfire). NOTE: Stream avulsion and other external factors related to precipitation change can play a factor at the project scale)	Watershed to project scale	50 to 100 years	Magnitude and duration of precip events	Broad scale subsidence due to reductions in groundwater levels, could impact buried utilities, and large scale infrastructure.

Breakout	Use Case	Hazard	Key Design Variable (i.e., Engineering Value)	Relevant ASCE Standards/Codes/MOPs	Primary Weather or Climate Input Value	Secondary Weather or Climate Input Value	Tertiary Input Value (may or may not be climate variable)	Needed Spatial Scale/Resolution	Design or Service Life Length	Necessary Data Characteristics (e.g., distribution, average, maximum, or minimum)	Notes for Report Narrative
Other Hazards											
Earth materials		Degraded soil strength (exceeding codified minimum values)	Soil strength	IBC							
Earth materials		Soil stress	Changing water/groundwater conditions	All geotechnical practice							
Earth materials		Erosion	Water velocity [no measurement at present]	EWRI (i.e., Flood Resistance Design) ASCE 7 - water velocity ASCE 24	Extreme precip events						
Earth materials		Wave action		ASCE 24 -14							
Earth materials		Overland flow velocity		ASCE 24 -14							
Earth materials		Scour		ASCE 24 -16, ASCE 45-16, 46-16, 47-16							
Earth materials		Coastal/urban drainage		ASCE 45-16, 46-16, 47-16							
Earth materials		Climate induced drought	Foundations/utilities (lifelines)								

Compound Flooding Including Inland and Coastal Flooding

Breakout	Hazard	Key Design Variable (i.e., Engineering Value)	Relevant ASCE Standards/ Codes/ MOPs	Primary Weather or Climate Input Value	Secondary Weather or Climate Input Value	Tertiary Weather or Climate Input Value	Needed Spatial Scale/Resolution	Design or Service Life Length	Necessary Data Characteristics (e.g., distribution, average, maximum, or minimum)	Notes
Compound flooding (coastal and lakes)										
Compound Flooding				Tidal stage (still water level)			NOAA NOS tide gauges provide 6-minute water level, hourly records, want longer timeseries of coastal and deeper ocean depth (instrument limited) NOAA working on coastal reanalysis (500-m grid resolution of tidal data along the US coastline, 40-50 years of data).			USGS-monitored water levels at some inland (near coastal) stations. (in addition to NOAA Tide Gauge network). Better historical data can better inform projections/modelling for higher sea levels in the future. Climate model guidance on SLR does not need to be such high resolution (that is, the changes are large spatial scale).
Compound Flooding				Storm surge (still water level)			Spatially consistent with tidal water levels (500m)			
Compound Flooding				Wave heights and velocity			Seconds (hertz)			USGS produces modeled and projected wave characteristics
Compound Flooding				Precipitation			5 - 25 km for coastal areas		Joint probability of heavy rainfall and storm surge (and other factors)	
Compound Flooding				River Discharge, Stage, Velocities			15 minute (typical USGS gauge). Need for river stage estimate between gauges during events.		Joint probabilty/conditional probability.	
Compound Flooding				Groundwater Level			High resolution (15 minute)			High groundwater table can limit soil storage capacity. More data and research on interaction with other processes needed.
Compound flooding (inland, tributary)										
Compound Flooding		River Stage (peak, duration)		River stage, local and upstream			USGS currently provides 15-minute timeseries, cannot find the peaks on some rivers due to instrument failure. Need better spatial resolution - reanalysis of river stage from observations (may not be possible from terrain, local rainfall patterns, not as easy as simply interpolating between stations!)		Give us 15-minute temporal resolution! * Note, this would be moving forward, not necessarily possible for historical timeseries * Note: the spatial resolution is highly dependent on the process. Downscaling is the problem, so higher resolution data that can be summed for larger grids is better than the reverse	USGS-monitored, NOAA station data, some areas do not have great coverage (near-coast, headwater/mountain)
Compound Flooding		Precipitation IDF		Precipitation			Increadibly localized storms in urban settings (even in complex terrain) can make modelling runoff and flooding risk very complex. In short, need better spatial resolution for very intense rainfalls that occur at small scales. Relevant to response times of urban drainage systems		Intensity, Duration, Frequency	Atlas 14, Atlas 15
Compound Flooding		Inundation depth/magnitude (maximum)					Inundation depth & spatial coverage!		Duration, Frequency, and Return Period (was this for inundation or for precipitation?	
Compound Flooding		Erosion potential		Landcover	Soil type					This may be a derivative variable (combination of soil type, precipitation intensity, land cover, etc.) Identified as especially important to GEO/Structure group
Compound Flooding		Percolation		Soil type						This is a factor in overland flow
Compound Flooding		Resevoir storage (including soil, aquifer)		Soil Water, reservoir levels						Have point measurements -- but to get values between measurements and for projections will it require a Water-balance method?

Breakout	Hazard	Key Design Variable (i.e., Engineering Value)	Relevant ASCE Standards/ Codes/ MOPs	Primary Weather or Climate Input Value	Secondary Weather or Climate Input Value	Tertiary Weather or Climate Input Value	Needed Spatial Scale/Resolution	Design or Service Life Length	Necessary Data Characteristics (e.g., distribution, average, maximum, or minimum)	Notes
Compound flooding (urban drainage)										
Compound Flooding		Heavy Rainfall		Precipitation			Spatial: 1 - 5 km for urban settings, 15-25 km resolution may be enough in simplified terrain. Synthetic data in both historical, present, and projected data may fill address this gap/need Temporal: Minutes		Non-environemntal Inputs: Drainage System Capacity (head loss due to drainage system eing overwhelmed)	Radar-based or Satellite-Based estiamtes may fill gaps between stations.
Compound Flooding		Water Levels at Outfalls		Water Level (SLR, Surge,Tides)						
Compound Flooding		Groundwater		Water Table level						Groundwater can exacerbate flooding by limiting uptake by soils. Groundwater also floods basements. Now the standard is to assume ground is saturated up to the flood elevation but that may not be true.
Compound Flooding		Storage Capacity (soils and Reservoirs)		Soil Moisture/Soil water storage capacity	Reservoir Levels					Reservoir Levels react to environmental factors.
Compound flooding (inland, groundwater)										
Compound Flooding		Water Table Depth		Water table depth					Water-balance method? Point source measurements?	Following hazards may include variables already outlined in inland tributary compound flooding USGS-monitored Water Table Depth was discussed in the Earth Materials Breakout.
Compound Flooding		Soil moisture		Evapotranspiration	Precipitation	Temperature				
Compound flooding (rain-on-snow)										
Compound Flooding		Total Runoff		Snow depth/melt	Precipitation	Antecedent River Stage				Rain on Snow and its effect on structural loads (ASCE 7) was discussed in the Snow Breakout.
Compound flooding (general considerations)										
Compound Flooding		Uncertainty					Uncertainty levels for all these variables is critical!			Many of these observations are distinct, but compound flood events include a confluence of distinct hydrologic processes. Should we ask for combined products or separate variables? It is difficult to provide historical timeseries if variables do not currently exist
Compound Flooding		Projections								Rare event is not often captured in historical observations (because it's rare), how do we use projections to have a better understanding of the increasing frequency of extreme events and the probable human (built & societal) impacts?

Appendix E. Climate Sensitive ASCE Standards and Manuals of Practice

Standard Number	Title	Sensitivity Grouping*
ANSI/ASCE 1-82	N-725 Guideline for Design and Analysis of Nuclear Safety Related Earth Structures	II
ANSI/ASCE 3-91	Standard for the Structural Design of Composite Slabs	I
ASCE 4-98	Seismic Analysis of Safety-Related Nuclear Structures and Commentary	III
ASCE 5-13 6-13	Building Code Requirements and Specification for Masonry Structures	III
ASCE 7-22	Minimum Design Loads for Buildings and Other Structures	I
ASCE 8-02	Specification for the Design of Cold-Formed Stainless Steel Structural Members	I
ANSI/ASCE 9-91	Standard Practice for Construction and Inspection of Composite Slabs	I
ASCE 10-15	Design of Latticed Steel Transmission Structures	I
ASCE 11-99	Guideline for Structural Condition Assessment of Existing Buildings	III, IV
ANSI/ASCE 12-13 13-13 14-13	Standard Guidelines for the Design, Installation, and Operation and Maintenance of Urban Subsurface Drainage	III, IV
ASCE 15-98	Standard Practice for Direct Design of Buried Precast Concrete Pipe Using Standard Installations	IV
ASCE 16-95	Standard for Load and Resistance Factor Design for Engineered Wood Construction	I
ASCE 17-96	Air-Supported Structures	I
ASCE 19-10	Structural Applications of Steel Cables for Buildings	I
ASCE 20-96	Standard Guidelines for the Design and Installation of Pile Foundations	IV
ANSI/ASCE 21-13	Automated People Mover Standards	I, IV
ASCE 24-14	Flood Resistant Design and Construction	II
ASCE 26-97	Standard Practice for Direct Design of Buried Precast Concrete Box Sections	III
ASCE 27-00	Standard Practice for Direct Design of Precast Concrete Pipe for Jacking in Trenchless Construction	III

Standard Number	Title	Sensitivity Grouping*
ASCE 28-00	Standard Practice for Direct Design of Precast Concrete Box Sections for Jacking in Trenchless Construction	III
ASCE 31-03	Seismic Evaluation of Existing Buildings	III
ASCE 32-01	Design and Construction of Frost-Protected Shallow Foundations	IV
ASCE 33-01	Comprehensive Transboundary International Water Quality Management Agreement	II, III
ASCE 34-01	Standard Guidelines for Artificial Recharge of Ground Water	III
ASCE 40-03	Regulated Riparian Model Water Code	III
ASCE 41-13	Seismic Evaluation and Retrofit of Existing Buildings	III
ASCE 43-05	Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities	III
ASCE 45-16 46-16 47-16	Standard Guidelines for the Design, Installation and Operation and Maintenance of Urban Stormwater Systems	II, III, IV
ASCE 48-11	Design of Steel Transmission Pole Structures	I
ASCE 52-10	Design of Fiberglass-Reinforced Plastic Stacks	I
ANSI/ASCE 56-10	Guidelines for the Physical Security of Water Utilities	II
ANSI/ASCE 57-10	Guidelines for the Physical Security of Wastewater/Stormwater Utilities	II
ASCE 60-12	Guideline for Development of Effective Water Sharing Agreements	II, III
ASCE 61-14	Seismic Design of Piers and Wharves	I
ASCE 62-16 63-16 64-16	Standard Guidelines for the Design, Installation, and Operation and Maintenance of Stormwater Impoundments	II, III, IV
ASCE 65-17	Calculation of the Saturated Hydraulic Conductivity of Fine-Grained Soils	III, IV
ASCE 66-17	Management Practices for Control of Erosion and Sediment from Construction Activities	II
ASCE 68-18	Permeable Interlocking Concrete Pavement	II, III, IV
ASCE 69-19	Standard Guidelines for Managed Aquifer Recharge	II, III
ASCE MOP 77	Design and Construction of Urban Stormwater Management Systems	II

Standard Number	Title	Sensitivity Grouping*
ASCE MOP 74	Guidelines for Electrical Transmission Line Structural Loading	I
ASCE MOP 153	Urban Stormwater Controls Operation and Maintenance	II
ASCE MOP	*Design Standards for Piers and Wharves* (under development)	III
ASCE MOP	*Compound Flooding* (under development)	II, III

*Sensitivity Groups: I - change in loading, II - change in surface hydrology (including flood extent or frequency), III - change in groundwater table height (including that related to sea-level rise), IV changes in temperature

Notes: The information is updated from ASCE Manual of Practice 140 *Climate Resilient Infrastructure: Adaptive Design and Risk Management*, Table B-1, with information from the ASCE Subcommittee on Climate Intelligence in Codes and Standards. Three-volume standards 12-13-14, 45-46-47, and 62-63-64 are published together though the middle "Installation" standard is not typically sensitive to climate and not counted in the total.

Appendix F. Group Photo