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ASCE-NOAA Workshops on Leveraging Earth System Science and Modeling to Inform Civil Engineering Design

Workshop I – Temperature and Rainfall (September 9 and 23, 2022)
Workshop II – Extreme Winds and Coastal Hazards (October 21 and 28, 2022)

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Foreword

This report is part of ongoing activities under a partnership between the American Society of Civil Engineers (ASCE) and the National Oceanic and Atmospheric Administration (NOAA). Initial steps towards the partnership were first announced in November 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 (Task Force). The Task Force, working with the ASCE Subcommittee on Climate Intelligence for Codes and Standards (CICS) 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 impacts of relevance to engineering practice as manifest in key ASCE standards and manuals of practice (MOPs).

In fall 2022 the Task Force organized a two-part workshop on Leveraging Earth System Science and Modeling to Inform Civil Engineering Design focused on three climatic hazards and one region of relevance to engineering practice. Part I of the workshop addressed extreme temperature and intense rainfall, and part II addressed straight-line winds and coastal hazards. *This workshop report is based primarily on the outcomes of structured discussion between climate scientists and engineers during the lengthy breakout sessions of those workshops*.

On February 1, 2023, the two organizations signed a Memorandum of Understanding (MOU) (available at: https://www.noaa.gov/sites/default/files/2023-02/MOU_between_the_American_Society_of_Civil_Engineers_and_NOAA.pdf), followed the next day by a leadership summit between the two organizations at which preliminary outcomes from these workshops were presented (National Institute of Standards and Technology (NIST) summary available at: https://nvlpubs.nist.gov/nistpubs/gcr/2023/NIST.GCR.23-042.pdf). The MOU more formally spells out the respective roles of ASCE and NOAA going forward and states as the major objectives of the partnership:

- Improve cooperation in development and delivering climate data, information, science and tools required by civil engineering 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.

ASCE is identifying its needs to incorporate the best available science into the next generation of civil engineering codes, standards, and manuals of practice. In turn, NOAA is identifying how it may be able to aid in satisfying these needs with its capabilities over both the near and long term. A formal collaboration between the Nation's largest provider of climate information and the world's largest civil engineering professional society will advance 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 codes and standards.

The overarching objective of this partnership between ASCE and 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 the changing climate. 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 and reduce design, construction, and maintenance costs as well as the costs of climate-related natural disasters.

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The Task Force populated workshop participants to achieve a roughly equal balance of ASCE and NOAA perspectives. The team acknowledges the commitment of ASCE and NOAA to gender and racial equity. The Task Force expresses its appreciation to the following individuals who volunteered their time to the workshop breakouts: Andrea (Andy) O'Neill, Andrew Earles, Andrew Hoell, Benjamin DeAngelo, Ben Kirtman, Bilal Ayyub, Bill Coulbourne, Billy Brooks, Brett Webb, Brian Parsons, Cherylyn Henry, Chris Cerino, Chris Jones, Chris M. Stone, Chris Stone, Craig Musselman, Craig Mussleman, Dan Barrie, Dan Walker, Daniel Cox, Daniel Wright, David Benson, David Easterling, David Rosa, Debbie Lee, Derek Arndt, Don Scott, Edward Yarmak, Emanuele Gentile, Erika Haldi, Farshid Vahedifard, Glenn Moglen, Greg Soules, Jamie Carter, Jane Baldwin, Jennifer Goupil, Jennifer Jurado, Jessica Blunden, Jessica Mandrick, Jin Hung, Joe Barsugli, John Allen, John Dai, John Duntemann, John Ingargolia, Jonathan Westcott, Kelcy Adamec, Kelly Mahoney, Ken Kunkel, Khaled Ghannam, Laura Bianco, Long Phan, Mari Tye, Mariam Yousuf, Mark Osler, Maya Hayden, Michele Barbato, Mitch Heineman, Oceana Frances, Patrick Barnard, Peter Vickery, Rachel McCrary, Robert Kopp, Robert Traver, Russ Vose, Sandra Pavlovic, Sarah Kapnick, Scott J. Weaver, Scott Weaver, Shirley E. Clark, Teng Wu, Terri McAllister, Tom Delworth, Tom Knutson, Victoria Morena, Yating Zhang, and Zach Labe. The Task Force also appreciates Meghan Edwards' copy editing and coordination support.

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Disclaimer

This is the first in a series of documents prepared by individuals from the ASCE, NOAA, and CTSM of UMD as part of a partnership to integrate climate science into civil engineering codes, standards, and MOPs. Any statements expressed in this report are those of the individual authors and do not necessarily represent the views of ASCE, NOAA, UMD, and other employers, which take no responsibility for any statement made herein. No reference made in this publication to any specific method, product, process, or service constitutes or implies an endorsement, recommendation, or warranty thereof by these entities. The materials are for general information only and do not represent a standard of ASCE, nor are they intended as a reference in purchase specifications, contracts, regulations, statutes, or any other legal document. These entities make no representation or warranty of any kind, whether express or implied, concerning the accuracy, completeness, suitability, or utility of any information, apparatus, product, or process discussed in this publication, and assume no liability, therefore. The information contained in these materials should not be used without first securing competent advice with respect to its suitability for any general or specific application. Anyone utilizing such information assumes all liability arising from such use, including but not limited to infringement of any patent or patents.

Executive Summary

The Workshops

The American Society of Civil Engineers (ASCE) and National Oceanic and Atmospheric Administration (NOAA) created a Task Force for Climate Resilience in Engineering Practice (Task Force) (More information in Appendix A). In fall 2022, the Task Force held two invitation-only workshops, entitled Leveraging Earth System Science and Modeling to Inform Civil Engineering Design. Workshop I covered temperature extremes and intense rainfall, and Workshop II covered straight-line winds and coastal hazards (such as flooding). Participants were drawn from authoring bodies of key ASCE standards and manuals of practice (MOPs), civil engineering practitioners familiar with engineering design covered by those guidance documents, NOAA climate scientists and modelers, and NOAA program managers responsible for shaping relevant research and service development.

Each workshop was centered on two concurrent breakout discussions focused on understanding how existing ASCE guidance documents, such as standards or MOPs, make use of related geophysical data sets and the sensitivity of the engineering applications to uncertainty in climate data or modeled projections. This was followed by discussion of the potential of climate science to meet these needs, the readiness of various NOAA data products to meet the needs of engineering practice covered by these guidance documents, and the potential development of updated or new data products. Despite the vast scope of the problem and the necessarily limited time for discussion, workshop participants were able to identify several areas where progress can be made. While the workshops focused primarily on identifying needs to support the ASCE standards process, there was a strong call from the practitioner community to develop ASCE-recognized best practices and approaches for interim use while standards or MOPs are updated.

The outcomes of these initial workshops are summarized below and in Table ES.1. More details on the workshop objectives and structure are provided in Appendix B. The outcomes of the workshop breakout sessions are provided in four chapters, corresponding to the three climate hazards and one region with their respective workshop breakouts.

For these initial workshops, the climate and weather hazards were discussed separately. The Task Force plans to extend this approach to other hazards. Options could include snow/ice loading, water table, and drought hazards, compound flooding, tornadoes, and downbursts, as well as the inherent interactions among hazards and resultant engineering design responses.

Table ES.1. Key Engineering Standards in Current Use, Climate Data Products, and Near-Term Opportunities Identified at the Workshops

	Climate Stressors			
	Temperature Extremes	**Intense Rainfall**	**Straight-line Wind**	**Coastal Hazards**
Civil Engineering Practice	Temperature impacts design variables related to materials, soils, hydrology, and system behavior	Rainfall intensity, duration and frequency are used in determining flood levels, structural loads, and in designing surface drainage	Wind speed is a primary design variable for determining structural loads	Sea level and lake level change, intensity frequency and extent of coastal storms, pacific wave climate, seasonal ice, and coral reef dynamics each influence flood characteristics
ASCE Standards and MOPs (and existing design requirement)	ASCE/SEI 32, ANSI/ASCE/T&DI 21, and five other standards Examples: Air Freezing Index (AFI) 100-yr Mean Recurrence Interval (MRI), daily max. temperature 50-year MRI, qualitative references in many standards	ASCE/SEI 7, ASCE/SEI 24, and six other standards and MOP 77 reference NOAA Atlas 14 Examples: 15-minute and 60-minute rainfall with 1 percent, 0.5 percent, and 0.2 percent Annual Exceedance Probability (AEP)	ASCE/SEI 7, 12 additional standards Example: Composite wind speed maps based on historic in situ measurement; 3-second wind gust for various MRIs up to 3000-year	ASCE/SEI 7, ASCE/SEI 7-22 Flood Supplement, ASCE/SEI 24 are key documents Example: flood depth for 100, 500, 750, and 1,000-year MRI
NOAA Products	NCEI AFI-100, Global Historical Climatology Network (station) and NOAA Monthly United States Climate Gridded Dataset (nClimGrid) (gridded) daily temperature, NOAA/GFDL projections	NOAA Atlas 14 NOAA Atlas 15 (under development) NOAA Hourly Precipitation Data (HPD)	NOAA process insight, boundary layer observations and modeling. Projections available from NOAA	Sea level change and coastal flood frequency estimates are available via the Interagency Sea Level Rise Task Force report.
Near-term Opportunities	Provide updated products and localized projections for statistics of monthly and daily temperature in usable formats. Engage with cold regions engineers.	Provide observational products on a readily accessible Web portal. Prioritize production of Atlas 15 Volumes 1 and 2, and their access via the Web.	Advance phenomenon-discriminated wind speed estimation. Coordinate wind data and expertise across NOAA, NIST, and other agencies.	Provide improved guidance and projections. Support advancements in Federal Emergency Management Agency (FEMA) non-regulatory products. Convene across agencies to bring research findings into practice.

Sources: ASCE 2013a, ASCE 2013b, ASCE 2014, ASCE 2001, ASCE 2017, ASCE 2018b, and NOAA n.d.
Note: Additional applications, products, and opportunities are discussed in the full text.

Extreme Temperature

- Temperature is a basic environmental variable that underlies many assumptions regarding the performance of natural and man-made materials. Consequently, it is widely considered in civil engineering design both in isolation and in combination with other variables. The review of ASCE standards identified more than a dozen standards that may be sensitive to changes in temperature extremes.
- Civil engineering practice areas covered by those standards include cold regions engineering, hydrology and hydraulics, structural engineering, and transportation engineering.
- Cold regions engineering was identified as particularly sensitive to anthropogenic temperature change. For example, soil mechanics vary by temperature, especially in regions where thawing permafrost results in loss of soil strength, or where the number of freeze-thaw cycles change under evolving climate conditions. Cold regions engineers are already adapting their practice to the changes that are already occurring.
- Observed and future projected temperature changes associated with changes in greenhouse gas (GHG) concentrations are relatively well-characterized processes, and substantial experience modeling future temperatures has been gained by NOAA and other major modeling groups.
- Atmospheric humidity was identified as an environmental variable that is strongly related to temperature and could logically be considered in tandem, though with potentially higher levels of uncertainty.
- Two specific temperature extremes were discussed – the 100-year return interval air freezing index (AFI-100), and the 50-year return interval daily maximum temperature.
- Temperature was identified as important for its influence on precipitation phase (rain,

Changing Hazards: Nonstationarity, Recurrence Intervals, and Exceedance Probabilities

Throughout this report you will find reference to both Mean Recurrence Interval (MRI), such as the 100-year flood depth, and Annual Exceedance Probability (AEP), such as the 0.1 percent, or 0.001 annual exceedance probability event for 15-minute rainfall. In a stationary climate MRI = 1/AEP, so a 1 percent event would be expected once in 100 years, on average. Recurrence intervals are also referred to as return periods. When considering climate change these quantities are no longer stationary in time and MRI becomes conceptually problematic. ASCE Manual of Practice 140: *Climate-Resilient Infrastructure: Adaptive Design and Risk Management* recommends using probability of exceedance (such as AEP) instead of recurrence intervals to characterize the changing probability of hazards. When discussing extant ASCE standards we attempt to follow the terminology and framing used in those standards. MRI appears frequently in this report and is emblematic of the fact that these standards were developed with an assumption of climatic stationarity. Where MRI appears here in a future-looking context (sometimes for convenience of description or reflecting discussion in the breakout sessions), it should be understood that a non-stationary exceedance probability is implied.

snow, or ice) for structural loading, though this was beyond the scope of the breakout.

- The need was expressed for more generalized temperature products including projections and focusing on extremes to support engineering design and risk assessment practice.
- Lack of data accessibility by engineers in usable formats and with pre-calculated engineering-relevant variables was identified as an impediment to use.
- Near-term actions could include:
    - Formation of a focus group on cold-regions engineering and temperature change related to ASCE/SEI 32.
    - Outreach to other engineering societies including American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) on daily temperature extremes calculations and Institute of Electrical and Electronics Engineers on the effect of temperature on power grids.
    - Updating existing NOAA products such as the NCEI AFI-100 product to reflect the most recent observations, providing a sound basis for developing future projections.
    - Supporting work to provide better access to observational products such as the NOAA gridded daily temperatures (nClimGrid-Daily).
    - Supporting work to provide gridded, localized, high-resolution climate model-based projections for key temperature variables of concern, including non-stationary exceedance values as a potential climate service in support of engineering practice.

Intense Rainfall

- Intense rainfall is a significant environmental condition of concern to engineering design. In addition to contributing to flash flood and other hazards, and affecting soil mechanics, intense rainfall events and the load they create on structures is a significant component of structural engineering design.
- The review of ASCE standards and MOPs identified eight standards and several MOPs (e.g., ASCE Manual of Practice 77: *Design and Construction of Urban Stormwater Management Systems*, ASCE 2018b) that may be sensitive to changes in rainfall intensity (see Table 3.1). Practice areas covered by these guidance documents include building and urban stormwater system design, including nature-based systems that may be subject to erosive velocities. MOP 77 is currently undergoing revision.
- Intensity-duration-frequency (IDF) and Probable Maximum Precipitation (PMP) estimates based on historical information are widely used in civil engineering design. However, estimates of how climate change may drive changes in these key parameters are not widely available at the spatial and temporal scales needed to support the design of climate-resilient infrastructure. Ongoing work to explore how models can be used to understand changes in precipitation under varying GHG scenarios may be leveraged to produce data products of value to civil engineers.
- Many ASCE standards refer the user to NOAA’s Atlas 14 (NOAA n.d.) for use in identifying critical intensities with respect to predefined storm durations and annual exceedance probabilities. In September 2022, NOAA’s National Weather Service (NWS) requested public comment on a proposed approach for updating Atlas 14. This update is referred to as Atlas 15. Atlas 15 will address two issues for Atlas 14, the lack of synoptic

nationwide coverage and the characterization of future changes in rainfall extremes on timescales relevant to engineering design.
    - As currently envisioned, Atlas 15 will be presented in two volumes, published concurrently. Volume 1 will replace Atlas 14 (historical data) and provide coverage across the United States including Hawaii, Alaska, and affiliated territories. Volume 2 will incorporate regional adjustment factors to account for the evolving climate.
    - The target completion date is 2026. Participants expressed a desire to see Atlas 15 Volume 1 advanced as rapidly as possible given the concern that the data in Atlas 14 are out of date and given the update cycle for ASCE/SEI 7.
- While NOAA has considerable available observational data, including historic hourly and subhourly records, many people are unaware of where to access the data.
- A recurrent theme from the engineering community was the need for sub-hourly (1-15 minute) precipitation for urban stormwater drainage (gray and green) and erosion calculations for construction sites.
- Near-term steps could include:
    - Greater efforts to make observational precipitation data more readily accessible and, perhaps more importantly, educate the practitioner community about their existence and utility. This could be a single interface similar to NOAA Atlas 14 but with access to historic data and where the user can specify the time increment of the data.
    - Efforts to synchronize the production of key data products with the timelines of users should be strengthened. For example, communication between the production team of NOAA Atlas 15 and the ASCE/SEI 7 update committee has been initiated.
    - Ensuring communication between NOAA and FEMA on the development of new precipitation products was also encouraged because of the importance of NOAA precipitation estimates to FEMA flood maps.
- Future steps could include:
    - Exploration of the use of re-forecast and hindcast data, in addition to radar and satellite observations to supplement observational records in data-sparse areas.
    - Participants supported having a diversity of products with differing methods to evaluate for developing engineering standards but recognized the additional complexity and communications challenges when more than one product is available.
    - Collaborative discussions are also needed to determine the best methods for communicating climate projection information for use by generalist engineers.
    - While there was no consensus around how to communicate future projections of extreme rainfall, estimates based on process understanding may ultimately prove to be an improvement over deterministic approaches.

Straight-line Wind

- Straight-line (non-tornadic) winds are an important subset of natural wind phenomena of concern to structural engineers and have been a historic focus of key ASCE guidance documents, such as ASCE/Structural Engineering Institute (SEI) 7: *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (ASCE 2013a).

- ASCE/SEI 7 includes sets of composite wind speed maps that integrate multiple meteorological sources of risk and produce risk assessments for four building risk categories and multiple wind speed mean recurrence intervals. Other ASCE and non-ASCE standards and codes reference ASCE/SEI 7 when providing guidance on engineering practice involving wind loads.
- Although ASCE/SEI 7-22 included a specific chapter on tornadoes in addition to winds, the current scientific understanding of how changes in the climate may affect changes in the frequency, geographic range, and seasonality of tornado storms is still in its infancy and therefore not part of the discussion at this time. The observational data and modeling products, as well as expertise needed to work on the climate-related aspects of this problem, are widely distributed across Federal agencies, modeling centers, and the academic and private sector communities. Within NOAA such expertise is also widely distributed across the agency.
- NOAA could explore collaborations within the agency to examine changes in meteorological phenomena driving wind speed change, and interdisciplinary observations-model efforts to produce improved wind projections for a variety of phenomena. Interagency partnerships and collaboration are important and may be accomplished through groups, such as the Interagency Council for Advancing Meteorological Services (ICAMS) and United States Global Change Research Program (USGCRP).
- Near-term and future steps could include:
  - Establish a consortium of wind-related experts across NOAA, including global modelers to boundary layer specialists, and wind profilers with observational data from NOAA and research institutions.
  - Consider consolidating and enhancing availability of NOAA’s wind-related data and assisting in the consolidation of additional relevant datasets through partnership with non-NOAA groups (e.g., National Center for Atmospheric Research (NCAR)).
  - Establishing additional venues for co-development of data products related to straight-line winds, under the leadership of NOAA and ASCE.
  - Focus on emerging work in the area of phenomenon-discriminated wind speed estimation. Possible products that could be developed using such estimations, where the wind risk associated with particular meteorological phenomena (e.g., tropical cyclones and extratropical cyclones) are estimated separately for each phenomenon and then later combined into a single wind speed map.

Coastal Hazards

- Sea level and lake level change, intensity frequency and extent of coastal storms, pacific wave climate, seasonal ice coverage, and coral reef dynamics each influence flood characteristics at the coast and are influenced by climate change.
- ASCE standards are of major influence in the treatment of weather and climate extremes in the design of buildings and other structures in the coastal zone. ASCE/SEI 7-22: *Minimum Design Loads for Buildings and Other Structures*, and especially its supplement, ASCE/SEI 7-22 *Flood Supplement*, and ASCE/SEI 24: *Flood Resistant Design and Construction*, provide insights into the treatment of various aspects on engineering design in coastal zone particularly with respect to the calculation of design loads resulting from flooding.

- Flooding is a manifestation of multiple processes operating under varying conditions and in interaction with diverse landscapes and topographies. Thus, the treatment of coastal flooding in engineering design reflects a high-level integration of multiple disciplines and data sets.
- The practicality of incorporating varying degrees of complexity into engineering standards is a manifest challenge, especially when dealing with coastal hazards. Compound flooding (e.g., the flooding that results when coastal storm surge occurs at the same time as high flows in coastal rivers and streams from significant inland rainfall) is of primary concern. Therefore, considering future conditions will require projections of future rainfall as well as sea-level change. Due to limitations of time and readiness of the standards process to address compound flooding, the Task Force concluded that compound flooding should be considered as the focus of future workshops.
- Federal investment in understanding sea-level rise has provided a relatively robust capability to estimate future sea levels, including the recent Interagency Sea Level Rise Task Force Technical Report (Sweet, et al. 2022).
- Near-term steps could include:
    - Focus on developing methods for projecting each individual phenomenon affecting coastal flood forces (hurricane winds, wave conditions, relative sea level rise, erosion potential, etc.) and for a reliable methodology to synthesize the individual results into the few variables that can be used by practicing engineers under the leadership of NOAA and ASCE.
    - Leverage partnerships with FEMA to ensure proper integration of climate science into FEMA's existing regulatory products (e.g., Flood Insurance Study and supporting materials) and non-regulatory products (e.g., mapping of the Limit of Moderate Wave Action). By working with FEMA, such efforts would build on familiarity of the engineering community with FEMA resources for relevant coastal flood hazard variables, thereby avoiding confusion within the practitioner community.
    - Convene across agencies to bring research findings into practice.

Overarching Issues

Workshop organizers and participants identified several overarching issues related to the use of future climate change projections, including the following:

- Identifying typical time periods for design life and associated projections for different engineering applications and appropriate data and methods to address these, ranging from near-term to 2150 and potentially beyond.
- The need for comprehensive geographic coverage and adequate spatial resolution levels for products that are developed.
- Ensuring accessibility of climate data, climate data products, and co-developed engineering data products that are usable by engineers, including the post-processing of climate variables and calculation of derived quantities relevant to engineering practice.
- Characterizing future climate hazards, including uncertainties, in ways that are useful to engineers in understanding risk and communicating risk to their clients, recognizing a range of plausible scenarios over time.

- There is also a need to further identify available NOAA observational and model information (e.g., GFDL Seamless System for Prediction and Earth System Research (SPEAR)) and NOAA labs/centers/line offices engaging in relevant work, and to further refine mutual understanding of gaps and research needs.
- Developing processes and data to address cross-hazard dependencies.
- Sustaining the ASCE-NOAA bi-directional technical and process pipelines.
- Sustaining support for continued climate product development and the integration of these products into the ASCE standards process.

Moving Forward

The discussions summarized in this report demonstrate the value of facilitated interaction between the civil engineering community, especially authors of guidance documents, and the scientific community focused on characterizing future weather and climate conditions. Maximum benefit could be obtained when such interactions become routine with a shared understanding of problems facing practicing engineers who engage in the planning and design of buildings and other infrastructure relying on key climate data, information, science and tools provided by NOAA and others. Formal channels for such communication are necessary and of strategic importance for transforming engineering practices for a climate-ready nation.

The results of subsequent pursuits based on the outcomes of the workshops may be used to generate technical basis documents as a foundation for other efforts for preparing guidelines and updating ASCE and other standards. Additionally, the workshop outcomes provide a credible basis for future efforts in preparing code cases for design standard updates in order to facilitate the ease of adoption. Future projects will include developing examples and case studies for different acceptable levels of risk for associated uncertainties, an assessment of the technical basis, adoption and cost implications, and providing references and sources.

Addressing the need for more formalized and sustainable channels of communication, a memorandum of understanding (MOU) between ASCE and NOAA was signed on February 1, 2023, paving the way for further bi-directional flow of information and expertise. An ASCE-NOAA leadership summit was held on February 1 and 2, 2023, organized by NOAA, ASCE, and the UMD CTSM at which the MOU was unveiled. Results from these workshops were also presented at that summit. The MOU and February 2023 summit details are provided in Appendix E of this report. Finally, outcomes from the workshops and February 2023 summit will inform future exchanges and conversations, including a pair of conferences fall 2023 focused on "future-ready" infrastructure: ASCE's 2023 Convention in Chicago in October and the ASCE Inspire conference in November.

1. Climate-Related Challenges in Engineering Practices

1.1. Background

From the 1980s to 2020, the average time between billion-dollar weather- and climate-related disasters decreased from 82 days to 18 days and occurred in all 50 states, the Virgin Islands, and Puerto Rico (NCEI 2023). In the United States, $145 billion in damages occurred in 2021 alone from weather and climate disasters (DOC 2022). The Fourth National Climate Assessment concluded that "[w]ithout substantial and sustained global mitigation and regional adaptation efforts, climate change is expected to cause growing losses to American infrastructure and property and impede the rate of economic growth over this century" (USGCRP 2018). As part of its Infrastructure Report Card series, ASCE recognizes that "Our nation is at a crossroads. Deteriorating American infrastructure is impeding our ability to compete in the global economy. Improvements are necessary to ensure our country is built for the future" (ASCE 2021).

In order to build sustainable, resilient, and climate-ready infrastructure, the practices of engineering planning and design require methods that account for a non-stationary climate over the decades-to-centuries lifetime of infrastructure. The incremental cost to plan and design climate-ready infrastructure is significantly less than retrofitting or replacing infrastructure that was designed for historic climate conditions. Decades of research and climate model development have identified the likely changes in many weather and climate hazards. However, the missing step is translating the state of scientific knowledge into a format suitable for engineering practices and design. Integrating climate change into planning and engineering practices will benefit public safety, national security, and fiscal objectives in all sectors of society and the economy.

An understanding of the imposed loads generated by weather- and climate-related processes on key components and systems is critical to decisions in planning and design. The calculation of design loads is a highly technical endeavor, and thus the vast majority of building codes in the United States and abroad rely on consensus guidance documents, such as those provided by ASCE. For instance, ASCE/SEI 7: *Minimum Design Loads for Buildings and Other Structures* is adopted into the International Building Code and is one of 43 ASCE standards currently identified as sensitive to weather and climate extremes. Thus, by updating the methodology underpinning ASCE standards to incorporate future weather and climate, ASCE could efficiently and quickly promote climate resiliency through hundreds of building codes nationally and globally and decrease risk to a significant segment of the United States population, including some of Nation's most vulnerable citizens (ASCE 2018a). ASCE has committed to addressing this challenge strategically and by its board resolutions.

1.1.1. ASCE Standards Needing Climate Considerations

At present, 43 of the existing 72 ASCE standards have been identified as potentially sensitive to change in weather and climate extremes (Table 1.1). Many of the remaining standards are insensitive to environmental conditions or cover engineering activities of such a short duration that changes in weather and climate extremes are not relevant. Appendix D provides more details.

Designing for anticipated loads relies on characterizing most-likely occurrences and extremes. Conversely, understanding how soil properties may change through time owing to drought, increased precipitation, or sea-level rise (SLR) may be of equal importance. Such considerations led to the recognition of four broad areas of sensitivity in design that are included in Table 1.1's "sensitivity grouping" column.

I. Changes in loading
II. Changes in surface hydrology (including flood extent or frequency, or inundation owing to SLR)
III. Changes in groundwater height or chemistry including those owing to SLR
IV. Changes in temperature

Table 1.1. ASCE Standards Identified as Sensitive to Changes in Weather and Climate

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/SEI 5-13 6-13	Building Code Requirements and Specification for Masonry Structures	III
ASCE/SEI 7-22	Minimum Design Loads for Buildings and Other Structures	I
ASCE/SEI 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/SEI 10-15	Design of Latticed Steel Transmission Structures	I
ASCE/SEI 11-99	Guideline for Structural Condition Assessment of Existing Buildings	III, IV
ANSI/ASCE/EWRI 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 (SIDD)	IV
AF&PA/ASCE 16-95	Standard for Load and Resistance Factor Design (LRFD) for Engineered Wood Construction	I
ASCE 17-96	Air-Supported Structures	I
ASCE/SEI 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/T&DI 21-13	Automated People Mover Standards	I, IV

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

Figure 1.1 depicts the hierarchy associated with ASCE documents that are typically prepared by volunteers. It illustrates the advancements in technical guidance for moving up the pyramid necessary to meet professional needs. These workshops contribute to meeting the emerging challenges facing practicing planners and designers as a first step toward developing a guidance document to address the direct impacts of a changing climate on infrastructure resilience.

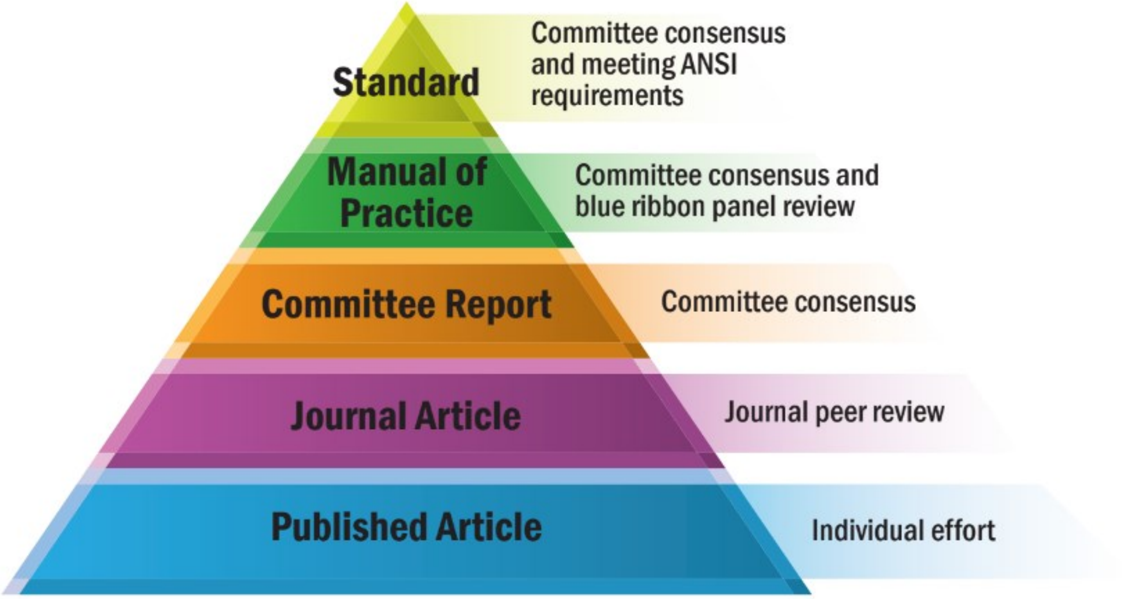


Figure 1.1. Hierarchy of ASCE Products

1.1.2. Primary Federal Climate Context

More than a dozen Federal agencies contribute to Federal climate science. The major interagency climate organization is the USGCRP. Established by Presidential Initiative in 1989 and mandated by Congress in the Global Change Research Act of 1990, USGCRP is to develop and coordinate "a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change." While each Federal agency in USGCRP plays a role in climate science, the NOAA is central to Federal efforts to promote the development and use of climate data and products in public and private sector activities. For example, NOAA maintains centuries of climate information, collects and interprets weather and climate information, and collaborates across the government to develop necessary resources, such as performing a major role in USGCRP and its National Climate Assessments. NOAA also plays an active role in numerous international climate activities, including the Intergovernmental Panel on Climate Change and the Global Framework for Climate Services initiative launched by the 2009 Third World Climate Conference. In recognition of the important leadership role NOAA plays, Congress in 2022 directed NOAA, in cooperation with the NIST, to "aid both Federal and non-Federal bodies to develop standards, building codes, and voluntary standards that take into account increasingly extreme weather events and other climate change challenges.”

2. Workshop 1 Outcomes: Extreme Temperature

The goal of these workshops was to identify engineering needs as framed in key climate-sensitive standards and to identify existing or potential climate datasets and products that could meet these needs. The summary that follows reflects the contributions and expertise of the workshop participants but is not intended to be a comprehensive needs or requirements assessment.

2.1. Defining Civil Engineering Need

Prior to the workshop, the ASCE CACC CICS reviewed ASCE standards for the use of atmospheric air temperature and related variables. Air temperature appears in many ASCE standards, both quantitatively and qualitatively, occasionally in isolation but more often in combination with other meteorological quantities. These can be divided into four areas of engineering practice as shown in Table 2.1. Table 2.2 depicts specific ASCE standards where temperature and directly related variables are mentioned; temperature dependent changes in other variables (e.g., snow) were not directly discussed in the workshop.

ASCE MOPs were not investigated for this workshop but will be investigated in the future. However, several examples of engineering practice beyond those included in the ASCE standards were discussed in the breakout sessions, such as impacts of temperature on railroad track buckling potentials, permafrost thawing, and on structural material degradation and longevity. Some examples of the specific temperature variables discussed were daily, monthly, and yearly extreme maximum and minimum temperatures as well as changing frequency of these extreme temperature events per year in the future.

Table 2.1. Engineering Uses of Temperature Information in ASCE Standards

Cold Weather Engineering	Hydrology and Hydraulics	Structural Engineering	Transportation Engineering
• Changes in locations subjected to frost action and freeze-thaw • Change in AFI-100 • Changes in frost depth • Changes in frost penetration • Melting of permafrost and keeping permafrost	• Soil temperature and humidity impact on permeability • Affect on water quality and best management practices designs • Changes to how inflow hydrographs are calculated • Fluctuation of water table depth • Accounting for frost action and freeze-thaw	• Thermal expansion of materials • Increased degradation, decay, and fatigue of materials • Accounting for frost action and freeze-thaw	• Change to 50-year MRI extreme daily temperatures • Changes in temperature and humidity for vehicle interior temperature design • Thermal expansion of materials

Table 2.2. Specific ASCE Standards with Temperature and Related Variables

No.	Complete Reference Number	Title	Temperature and Related Variables Referenced in the Standard
11	ASCE/SEI 11-99	Guideline for Structural Condition Assessment of Existing Buildings	temperature, weather data, weathering data, environmental variables, freeze-thaw
12 13 14	ANSI/ASCE/EWRI 12-13 ANSI/ASCE/EWRI 13-13 ANSI/ASCE/EWRI 14-13	Standard Guidelines for the Design of Urban Subsurface Drainage	freeze thaw, water table, temperature, humidity, soil moisture content, evapotranspiration rates
21	ANSI/ASCE/T&DI 21-21	Automated People Mover Standards	low, high, mean values of temperature, humidity, 50-year return value
45 46 47	ASCE/EWRI 45-16 ASCE/EWRI 46-16 ASCE/EWRI 47-16	Standard Guidelines for the Design of Urban Stormwater Systems	temperature, freeze-thaw, water table
20	ASCE 20-96	Standard Guidelines for the Design and Installation of Pile Foundations	thermal stresses, freeze-thaw cycles
32	ASCE/SEI 32-01	Design and Construction of Frost-Protected Shallow Foundations	temperature, freeze thaw cycles, 100-year air-freezing temperature return period, frost depth, mean return period air-freezing index, mean annual air temperature
62 63 64	ANSI/ASCE/EWRI 62-16 ANSI/ASCE/EWRI 63-16 ANSI/ASCE/EWRI 64-16	Standard Guidelines for the Design, Installation, and Operation and Maintenance of Stormwater Impoundments	temperature, freeze thaw, water table, humidity

2.1.1. Temperature Related Priorities

The workshop breakout could not cover all of the widespread but varied use of air temperature in engineering noted above. Consequently, the workshop breakout focused on three areas in ASCE standards or engineering practice where temperature is the dominant or exclusive factor to begin to drive collaboration with NOAA. These three areas are below.

- ASCE/SEI 32, and in particular the calculation AFI- 100 and other temperature-based quantities such as Design Frost Depth, Air Thawing Index (ATI) related to cold regions engineering, and freeze-thaw cycles in soils.
- ANSI/ASCE/T&DI 21, the 50-year return interval daily maximum temperature (computed according to the ASHRAE Handbook (ASHRAE 2021).
- Development of a general purpose observational and projected temperature dataset with derived quantities characterizing extremes that would broadly serve engineering practice.

ASCE/SEI 32 applies to cold regions with seasonal ground freezing. More specifically, the standard applies for areas where the 100-year MRI value of the air freezing index AFI-100 less than 4,500°F-days and where the annual mean temperature is above 32°F (0°C). AFI is the annual accumulated degree-days below freezing for a defined cold season. However, there would be a broader application of temperature data beyond ASCE/SEI 32 to regions that are experiencing thawing permafrost and changes to the freezing and thawing season. One emerging hazard is the larger seismic response as permafrost thaws leading to changes in soil liquefaction. Because of the rapid rate of warming in the Arctic, these considerations may provide a high-profile example of the emerging threats from climate change's extreme temperatures.

In ANSI/ASCE/T&DI 21, the design of Heating, Ventilation, and Air Conditioning (HVAC) systems of automated people movers, as well as for the operation of propulsion and braking system and substation equipment, utilizes the 50-year return value for highest maximum and lowest minimum extreme daily temperature under naturally occurring combination of temperature and humidity. Air temperature also appears in this standard in conjunction with humidity and direct solar radiation. Many of these other variables are described in the ASHRAE Handbook.

A general temperature product might include current and projected values for the following:

- Air temperature: daily timescale, average, extreme, probabilities of exceedance, and return values for various return intervals,
- AFI: mean annual, minimum annual, maximum annual, and non-stationary 1 percent AEP (replacing the 100-year stationary MRI),
- Two percent AEP value (replacing the 50-year return value) for daily maximum and minimum temperature,
- Heat events: frequency (events/year), duration (days/event, number of days above a threshold), and amplitude (°C or °F), and
- Provide exceedance probabilities (instead of return periods).

For some uses the changing probability of exceeding a fixed threshold may be more useful than the changing level for a given probability. It should be noted that projections referenced to climate change levels in addition to specific time horizons are for either with respect to pre-industrial level or some recent reference period.

2.1.2. Spatial scales

In general, climate data is desired at the project site or as near as possible. However, that is not always available, even in current practice. Nearby station data is often used. The use of gridded daily observational climate data (such as NCEI's nClimGrid-Daily) may facilitate the development of temperature products analogous to the ASCE/SEI 7 hazards tool for precipitation, where NOAA Atlas-14 values (interpolated to a resolution of 30-arc- seconds or about 1 kilometer (km)) are returned to the user for a given location.

During the discussion of downscaled climate projections, people noted that there is no clear guidance on which of the many products available are best for which purposes. The current/near future state of GFDL climate modeling is at 25 km resolution (before downscaling). Generally, having the foundational dataset at 25 km spatial resolution (from which local values could be extracted) may suffice for many purposes. 25 km is adequate for temperature because of the generally large-scale structure of temperature change patterns. Near coastlines and in very mountainous terrain can be exceptions and practitioners should exercise extra care in these situations.

2.1.3. Temporal scales

Temperature products described in the ASCE standards are often based on statistics derived from historical daily timescale data, including daily minimum and maximum temperature. These statistics include means and extreme values – the 1 percent AEP (100-year MRI) event, for example – and are currently computed over some recent epoch, perhaps 10 to 30 years, where 30 years represents the “climate normal” period. A longer period of record may be used in practice if the engineer has access and deems it necessary to capture rarer statistics. A workshop participant gave an example of using monthly projected temperatures for projecting future freezing indices.

For projections, one may consider epochs every 20-25 years in the future, or other treatments of non-stationarity, though the recommendation of future periods should be coordinated across all climate variables. The question arose of what to do after 2100 when fewer climate model projections are available and “deep uncertainty” dominates.

2.1.4. Sensitivity to Uncertainty

The sensitivity of the engineering application to uncertainty in temperature projections varies on the particular application and geographical region. One engineer expressed an opinion that air temperature changes were not likely to have a significant impact on many structural engineering design problems compared to loads from seismic, wind, rain, flooding, and snow. For problems where this is the case, uncertainty in local temperature change may not matter significantly. For other problems such as the location of areas and depth of seasonal freeze-thaw, the uncertainties may be large, particularly in the Arctic and sub-Arctic where average temperature changes have been and are projected to be the largest. It was noted that certain engineering applications, such as in power transmission, the impacts of periods of extreme high and low temperatures are already impacting design criteria. These issues are not related to specific ASCE standards.

2.2. Engineering Use Cases

Several use cases were identified beyond those in specific ASCE standards. First is the need for temperature projections in the engineering analysis of material degradation (decay, corrosion, fatigue, cracking, etc.). As an example, air temperature and humidity were identified as factors in the predicted lifetime of materials in bridge design (Zhang, et al. 2022), and both climate variables are generally projected to increase in coastal areas. Significant conversation centered on the impact of temperature change on soil properties. Major areas of discussion were the effects of temperature combined with water in the soil column, the effect of prolonged drought on the strength of the soil column, and other geotechnical engineering concerns. Air temperature is often used as a proxy for soil temperature. The breakout participants requested the development of a soil temperature product.

Several ASCE standards refer to soil hydrology or other “non-flood” hydrology where the effects of temperature on the water balance are more salient than for rapid flooding events, where precipitation intensity and amount dominates. Examples include the importance of temperature for evapotranspiration, the impact of drought and long-term aridification on water table levels, and the effect of soil permeability on stability of earthen embankments. The effects of warming temperature combined with precipitation was seen as significant, including the potential for an increase in the frequency of rain-on-snow events and the potential for changing snow loads for building design.

The breakout group also acknowledged the importance of air temperature changes to standards outside of ASCE standard and guidance documents. Examples included electrical equipment, transmission lines, HVAC, class 1 railroads, and roads. A longer-term goal of these efforts could be to work with other standard organizations, such as the Institute of Electrical and Electronics Engineers and American National Standards Institute (ANSI) on a coordinated approach to incorporating temperature changes.

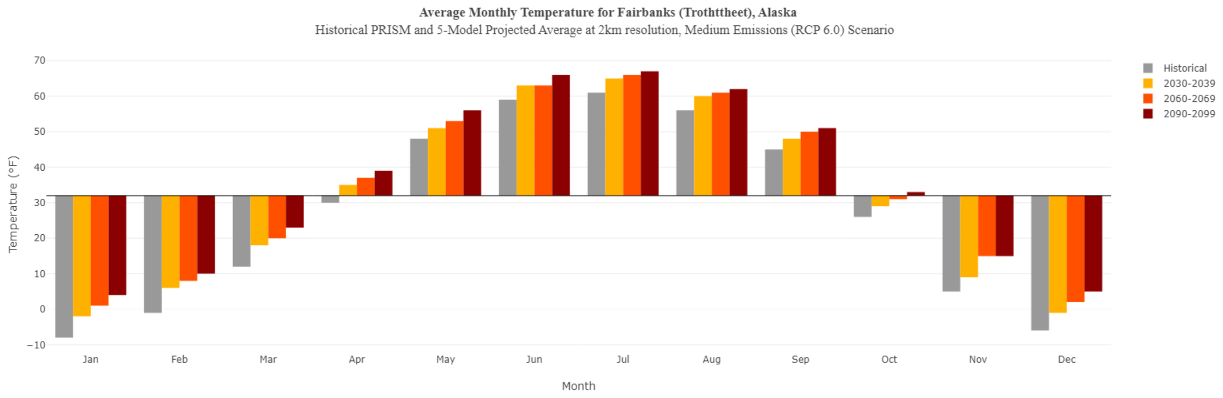
2.3. NOAA Climate Products, Information, and Potential Approaches

2.3.1. Air Freezing Index and ASCE/SEI 32 (Design and Construction of Frost-Protected Shallow Foundations)

A specific use case relating to ASCE/SEI 32 may provide a template for the development of a product. One participant explained how he uses climate projection data in his practice in Alaska. Local observation data is obtained from regional sources, such as Scenarios Network for Alaska + Arctic Planning (SNAP) or is otherwise acquired by engineers. Freezing and thawing indices are then computed for their design purposes. The workshop participant currently uses the community charts tool from SNAP to obtain monthly temperature projections such as that illustrated in Figure 2.1 (University of Alaska n.d.). These projections illustrate the longer thaw season and the shorter freezing season comparing historic data with projections for 2030-2039, 2060-2069, and 2090-2099. The workshop participant also noted that no one he was aware of looks past 2100. It was noted that uncertainties are not shown on the SNAP website beyond the differing emissions scenarios and would be a valuable addition. A product that served this need could likely be used in engineering practice as soon as it is developed.

ASCE/SEI 32 characterizes aleatoric uncertainty by referencing the 100-year MRI value for the AFI. Workshop participants also expressed concerns that the “weather” not be neglected. For example, the year-to-year variability in AFI, as well as possible short term variation such as few weeks of freezing events, can cause major issues. For example, a short duration freeze recently occurred in the state of Georgia that caused road damage. The minimum and maximum annual values of AFI in the observed record were also seen as potentially useful. In addition, it was suggested by one participant that an index based on the last date of freeze may capture the potential for uncommon but damaging freezes.

NCEI provides data for freezing indices including AFI-100 for Continental United States (CONUS) stations using 1981-2010 data. Work can be done to update the NCEI data to the current climate normal period, and more robust products in this space would be helpful. ATI can easily be added to the dataset as well as minimum and maximum historical values. The practice for future projection outlined by a participant could also be implemented, provided the larger issues of characterizing epistemic/combined uncertainty of projections is agreed upon.



These plots are useful for examining possible trends over time, rather than for precisely predicting values.

Figure 2.1. Monthly Projected Temperature for Fairbanks, Alaska for Historical and Four Future Time Periods under the Coupled Model Intercomparison Project Phase 5 (CMIP5) Representative Concentration Pathway (RCP) 6.0 Climate Scenarios (University of Alaska n.d.)

2.3.2. 50-year MRI temperature events and ANSI/ASCE/T&DI 21 (Automated People Movers Standards)

ANSI/ASCE/T&DI 21 references the ASHRAE Handbook for calculation of the 50-year return value of highest maximum and lowest minimum extreme daily temperature. That handbook recommends using the NOAA Integrated Surface Data of hourly station observations, which is a relatively sparse network that has hourly measurements. The data available at http://ashrae-meteo.info/v2.0/ is for the nearest available station, which is typically an airport or other automated weather station. The workshop attendees did not verify that this is what is used in practice. Further research is needed to determine whether daily maximum and minimum values would be sufficient for ASCE needs, as this would enable the use of a much denser network of stations and possibly gridded observational data. The use of reanalysis data was considered by ASHRAE and recommended only when consulting an expert meteorologist because of potential biases with respect to the station data.

ANSI/ASCE/T&DI 21 characterizes aleatoric uncertainty by referencing the 50-year MRI value as defined in the ASHRAE Handbook. The 2021 ASHRAE Handbook version recommends using a recent 26-year period of data, to minimize the effect of past trends. Extreme value theory is then used to estimate the 50-year MRI value. Specifically, a Gumbel extreme value distribution fit is made using the method of moments, and afterwards return values of various MRIs can be calculated.

The 50-year MRI value of daily maximum and minimum temperature and going forward, the non-stationary 2 percent AEP value, can be computed as part of a specific or general-purpose temperature dataset based on station or gridded historical observations and climate model projections. Other meteorological quantities referenced in ANSI/ASCE/T&DI 21 via ASHRAE may be more difficult to obtain from climate model output as they are based on hourly data, which is considered somewhat less reliable from climate models and would require more evaluation.

In general, it was agreed that calculation of temperature indices based on daily or monthly data are technically straightforward once trust is gained in the underlying data for either historical or projected data.

2.3.3. Data Access, Availability, and Impediments to Use

Potential impediments to the use of climate products were discussed including difficulty of access and the overall difficulty for engineers to deal with the types and magnitude of uncertainty in climate projections. Currently, it is difficult to get access to observed and projections data. Practitioners would appreciate having easier-to-use portals. Within NOAA and elsewhere, use of projection data for temperature requires considerable knowledge and specialized skill to access. NCEI has available historical observed data that is up to date. NOAA/PSL has provided a web interface to some projections data at https://psl.noaa.gov/ipcc/ from multiple modeling centers, which is not tailored to ASCE needs.

Workshop discussion focused on the feasibility of using native climate model resolutions such as the 25 km resolution of the latest GFDL-SPEAR high resolution model. The general sentiment among breakout participants was that 25 km resolution is a good starting point and probably sufficient for temperature changes. However, local scale resolution (for example, about 3 km) is useful to study at county level and community level. Currently, some projects have to downscale the data from general circulation models (GCMs) themselves. Familiarity in the way data is provided would also be helpful. Participants noted the existence of many downscaled climate projection products. One example of a more user-friendly portal is Cal-Adapt. Cal-Adapt takes data from NOAA and other modeling centers and provides a downscaled product for users (https://cal-adapt.org/tools/). Workshop participants did not discuss further specific downscaling methods or downscaled datasets. One engineer noted that uniformity of gridding is not essential, but the gradient/rate of change of variables (spatially) is more relevant for some problems, e.g., Hurricane Katrina's impacts.

2.3.4. Climate Projection Uncertainty

Forward-looking uncertainty has to deal with not only future weather variability but also uncertainty in emissions, from climate models, and potentially from downscaling. This is an overarching issue that affects the use of climate projections in general, and the workshop participants agreed the treatment of this uncertainty should be dealt with as a whole and not for a single climate variable.

The uncertainty around sea level rise may provide an analogy to the uncertainty around temperature projections as the direction of change is generally known but the magnitude of change depends on many factors with much uncertainty by the end of the century. Some design guidance addressing uncertainty has been developed for sea level rise in terms of climate and the associated risks as well as design life. Much current design guidance is coming from the state level. A workshop participant gave this example from New Hampshire: https://scholars.unh.edu/cgi/viewcontent.cgi?article=1210&context=ersc.

Past efforts at using climate projections in engineering have been hampered by engineering practice getting lost in the complex uncertainties of climate projections. Several ideas were put forward by the breakout participants to address the complexity. The adoption of a rating system for different risk levels was suggested. One specific idea put forth was that adopting climate resilience levels, such as platinum, gold, and silver, by analogy to Leadership in Energy and Environmental Design or LEED standards, might help engineering to cut through some of the complexity. One of the rating systems that addresses this is the Institute for Sustainable Infrastructure's Envision rating tool (https://sustainableinfrastructure.org/envision/overview-of-envision/). It is a framework with the goal of increasing the resiliency, preparedness, and long-term viability of civil infrastructure, by using a broad range of social, economic, and environmental indicators, and providing climate-ready, fiscally responsible, and resource-efficient infrastructure. The concept of community risk rating also exists in seismic space and might be adapted into climate space.

2.3.5. Additional Potential Products

In addition to the specific indices mentioned above, another product identified as potentially helpful but may not address specific ASCE standards would be an interactive tool with geographic information system or GIS to pull historical observations and projections of various air temperature data and derived quantities including exceedance probabilities.

The potential for products related to other meteorological and hydrological parameters that are influenced by temperature in ASCE standards noted in Table 2.2 was briefly discussed:

- ASCE/SEI 11; ANSI/ASCE/EWRI 12, 13, and 14; ANSI/ASCE/T&DI 21; and ASCE/EWRI 62, 63, and 64 on Humidity. Because air humidity is considered along with air temperature in a number of standards, the expansion of the temperature datasets to include a humidity dataset should be considered. It is a natural companion to air temperature. Humidity data is in general less widely available and of lesser accuracy than air temperature data. A gridded historical humidity dataset is being developed at NCEI, and several reanalysis products are available as well for the historical period. Climate model humidity output is also available; however, its reliability would need to be a topic of research.
- ASCE/EWRI 62, 63, and 64 on Stormwater Impoundments. Inflow hydrographs, specifically the Hydrological Simulation Program - FORTRAN hydrologic model and ASCE/EWRI 62, 63, and 64 (Stormwater Impoundments); ASCE/EWRI 45, 46, and 47 (Urban Stormwater Systems); and ANSI/ASCE/EWRI 12, 13, 14 (Urban Subsurface Drainage) Water table depth and seasonal fluctuations. Getting projections to support these standards would likely require hydrologic modeling where the sensitivity of evapotranspiration to temperature is taken into account along with a unified set of other meteorological variables typically used in hydrologic modeling at these temporal scales. Hydrologic modeling for current and projected climates is a very active area of research and application. This topic is beyond the scope of the workshop's temperature breakout and could be a separate topic for future workshops.

- ASCE/SEI 7. Warming temperatures combined with precipitation, including rain on snow events, influences snow and ice loads.

2.4. Process Going Forward

An idea discussed for housing and distributing such products is that NOAA could create the meteorological products, and ASCE could host the product in a way that meets the needs of ASCE. The ASCE 7 Hazards Tool was seen as a promising model.

Additional data that NOAA could supply for engineer use include a tailored downscaled product (such as AFI) or a 25 km GFDL SPEAR model-based product. These will be of greatest benefit when the evaluation of geographic and historical fidelity against observations, which is typically performed by modelers, is communicated to users. Uncertainty quantification was also seen as critical, including a retrospective assessment of modeling uncertainty. One participant offered as an example a website where the range of past projections of models in the Arctic is compared with observed trajectories. Such a template could be replicated for other regions and variables. Global scale uncertainty is quantified in projections and climate assessments such as the Intergovernmental Panel on Climate Change Sixth Assessment Report; however, it is important that the range of uncertainty is presented on regional scales and that the information is presented clearly.

Some near-term actions were identified for ASCE/SEI 32 and ANSI/ASCE/T&DI 21, including getting input from ASHRAE as data for temperature projections is considered and engaging ASCE Cold Regions Engineering Division and in particular the Frozen Ground Committee on updating AFI-100 and other potential products.

The following are suggestions on the process for keeping this collaboration going:

- A focused co-development group or groups would be a way to work together.
- There is a need for resources to not only support development but also maintenance and regular updating and improvement of climate products to support this effort.
- NOAA has strategic plans (Climate Ready Nation) with the intent of developing data and products to support the delivery of climate services for adaptation.
- NOAA participation would likely be across multiple labs/centers, such as those represented at the workshops: NCEI, GFDL, and PSL. Having Regional Climate Service Directors and/or Climate Adaptation Partnerships (CAP, formerly Regional Integrated Sciences and Assessments or RISA) teams could help match needs to local knowledge.

3. Workshop I Outcomes: Intense Rainfall

The goal of these workshops was to identify engineering needs as framed in key climate-sensitive standards and to identify existing or potential climate datasets and products that could meet these needs. The summary that follows reflects the contributions and expertise of the workshop participants but is not intended to be a comprehensive needs or requirements assessment.

3.1. Defining Civil Engineering Need

The need of civil engineering practice for climate related information was initially established by examining pertinent ASCE standards and MOPs for their inclusion of precipitation (specifically rainfall) related variables. Particular attention was paid to the tabulated values, observational sources, and other numerical input of relevance to civil engineering planning, design, and operations.

The review of standards and MOPs has been, and will be further, supplemented by the ASCE CACC and the CICS subcommittee. ASCE MOPs were not investigated prior to this workshop but will be reviewed by CICS in the future. From the initial evaluation, the majority of rainfall related variables in ASCE standards are limited to intensity duration parameters as listed in Table 3.1. However, the workshop participants noted that flood depths are required for design but currently are obtained from FEMA floodplain models or similar approved by the community, which are in turn dependent on precipitation. Furthermore, in many urban systems, people only have to identify the likelihood of exceedance for a specific storm depth and duration instead of overland runoff occurring after drainage capacity exceedance and the associated pluvial flooding. Recent problems with storm drainage exceedance have led more jurisdictions to consider the need for urban flood maps and updated probabilities of failure from very intense short duration rainfall events.

Workshop attendees recommended that FEMA and other relevant organizations be better integrated in discussions between ASCE and NOAA to inform updates to flood mapping and resultant flood loads, including those from pluvial flooding.

Breakout participants also highlighted that MOP 77: *Design and Construction of Urban Stormwater Management Systems* is specific guidance that supports ASCE/EWRI 45 and ASCE/EWRI 62. MOP 77 is currently under revision, which is the first set of updates in 30 years. MOP 77 illustrates the type of supporting guidance offered by ASCE to the practicing community for their design.

Soil mechanics, specifically with respect to foundation and embankment design such as ASCE 20, do not make direct reference to rainfall and, as such, did not form part of the workshop discussions. However, a need was identified to understand the probability of failure as a result of fluctuating soil moisture conditions arising from increased frequency of intense rainfall.

Table 3.1. ASCE Standards Making Reference to Rainfall

No.	Complete Reference	Title	Rainfall Related Variables Referenced in the Standard
7	ASCE/SEI 7-22	Minimum Design Loads for Buildings and Other Structures	*Section 8.2* **15-minute** rainfall at 1 percent Annual Probability (Risk Categories (RC) 1 and 2); 0.5 percent (RC3); 0.2 percent (RC4); Refers user to Atlas 14
24	ASCE/SEI 24-14	Flood Resistant Design and Construction	Indirect use of rainfall – refers to community adopted flood maps (often provided by FEMA)
45 46 47	ASCE/EWRI 45-16 ASCE/EWRI 46-16 ASCE/EWRI 47-16	Standard Guidelines for the Design of Urban Stormwater Systems	*Section 4.1.6* **60-minute** rainfall for areas less than 80 hectares *Section 4.1.7* **24 hour** rainfall 50 percent Annual Probability
62 **63** **64**	ANSI/ASCE/EWRI 62-16 ANSI/ASCE/EWRI 63-16 ANSI/ASCE/EWRI 64-16	Standard Guidelines for the Design, Installation, and Operation and Maintenance of Stormwater Impoundments	*Section 8.2.1* 1 percent annual probability **6, 12, 24, 96 hour** durations. Refers user to Atlas 14 and to Natural Resources Conservation Service
67	ANSI/ASCE/EWRI 66-17	Management Practice for the Control of Erosion and Sediment from Construction Activities	Indirect use of rainfall - refers to state guidance for the exceedance probability (return period) to be used to design stable slopes and channels. Rainfall energy (calculated from multi-year 30-minute peak intensity or estimated based on total rainfall depth and total storm duration)

3.1.1. Geophysical Parameters

The breakout group focused solely on rainfall rather than other aspects of precipitation (e.g., freezing rain, snow, or hail). While there is a widespread but varied application of rainfall parameters and statistics in engineering, the geophysical parameters over which ASCE has control for design and operations are primarily affected by the intensity and duration of different storms. This is noted in bold type in Table 3.1. Other design components such as wind-blown rain (on cladding) or above ground drainage are controlled by other design codes such as the International Code Council (ICC) plumbing code. Impacts of rainfall and soil moisture on subsurface drainage are outlined in ANSI/ASCE/EWRI 12, 13, and 14, but rainfall information provided by NOAA is not explicitly used in the design of these subsurface systems. Secondary effects of intense rainfall, such as flood levels and soil moisture, are also outlined in non-ASCE documents.

ASCE/SEI 7, 45, and 62 refer the user to NOAA's Atlas 14 for use in identifying critical intensities with respect to predefined storm durations and annual exceedance probabilities. Workshop participants brought up the difference between total rainfall volume (affecting fluvial flooding and stormwater pond design) and peak intensity (affecting urban pluvial flooding when either green or gray infrastructure system capacity may be exceeded), resulting in flooding outside of designated floodplains.

3.1.2. Temporal and Spatial Scales

Breakout participants discussed the likely temporal and spatial scales associated with the rainfall parameters outlined in Section 3.2. The workshop assumed that the use of ASCE standards and procedures applies to any location within the United States or Puerto Rico.

Specific facilities or individual structures utilize point estimates of rainfall at different time intervals, as specified by the different code elements listed in Table 3.1. Point estimates are generally identified from Atlas 14 or Atlas 14 derived products. Urban areas utilize the characteristic time for water to flow from a sewershed boundary to the gutter inlet or inlet to the stormwater control measure. These times may be as short as five minutes and typically do not exceed 30 to 60 minutes. Workshop participants felt that there is insufficient attention paid to the spatial and temporal scales relevant for urban flooding. Workshop participants would like to see urban flooding reflected better in design guidance and associated maps for decision making.

In contrast, network systems are dependent on rainfall estimates in a spatial context. Workshop participants expressed a concern that some practicing engineers may use point estimates as inputs to spatial networked models with a view that using a maximum point estimate value throughout a network would result in a conservative design. Contributing areas for urban drainage systems could be in the order of two acres or less, but this could range up to hundreds of square miles when considering the complete watershed upstream for fluvial drainage basins. At that larger scale workshop participants agreed that the projects were more likely to need more site-specific attention to climate change. The more "standard" projects that were the focus of this workshop would leverage flood levels from FEMA flood maps, or similar as approved by the jurisdictional authority, and so not require large areal estimates of rainfall.

3.1.3. Sensitivity to Uncertainty

Breakout participants were asked to consider the impact of different sources of uncertainty in climate projections (i.e., epistemic, model, and emission related). It was pointed out that while statistical uncertainty is incorporated in low probability event estimates, other sources of uncertainty, e.g., in the observational measurements themselves, may not be. Many current codes do include some uncertainty (e.g., some sources of uncertainty are included in determining the 15-minute rainfall with 1 percent probability of exceedance). The central question is which sources of uncertainty should be included and how those uncertainties should best be quantified (e.g., if too many sources of uncertainty the 1 percent probability of exceedance may be difficult to rationalize). Incorporation of broader parameter estimates will require further collaboration and discussion with the standard setting committees.

Participants expressed concern that they do not know how the temporal and spatial distributions of rainstorms are changing. Environment and Water Resources Institute of ASCE (EWRI) representatives noted in a listening session in March 2022 their constituents asked for guidance on how to incorporate precipitation changes into their designs. While ASCE/SEI 7 specifies 15- and 60- minute durations ranging from 100- to 500-year return period storms, participants would like to know what would be the impact of using those specific storm definitions under climate change scenarios. It was suggested that involving economists will be necessary to support engineers in understanding the implications of increased risk conservatism.

3.1.4. NOAA Precipitation Atlases in ASCE Standards

In general, the ASCE standards point to Atlas 14 as the primary data source for rainfall related designs. It was noted that nationwide observational estimates produced by non-NOAA entities, but relying on NOAA-NWS data and storm records, can be expected to be consistent with NOAA products, such as Atlas 14. The general consensus of breakout participants was that NOAA is considered to be the source of reliable data, and rainfall products or methods to incorporate climate change that have been or will be developed by NOAA are the *de facto* standard. They were very keen on the approach to bringing Atlas 15 into the public domain and updating it to support designers.

3.1.5. Additional Use Cases

Participants identified that wind driven rainfall is critical for cladding design but may not be captured in ASCE. Other entities are working to address these issues (e.g., Blocken and Carmeliet n.d.). Another use case involves primary building drainage, which refers to the ICC plumbing code, while ASCE/SEI 7 rainfall design criteria covers the secondary roof drainage. The two code systems need to be compatible. If there is substantial change to the rainfall intensities, participants suggested it would be worth proposing updates to the primary drainage intensities through ICC hearings, but it is unlikely that any updates would be included in this revision cycle unless they were incorporated in the commentary section.

Participants stated a need for improved guidance on areal reduction factors and application for temporal distribution patterns. In particular, participants noted that the cascading impacts of pluvial flooding can be onerous, resulting in damage from prolonged soil saturation and inundation outside the designated flood zone. As such, there is a growing need for pluvial flood guidance that addresses the downstream consequences of drainage exceedance.

Breakout participants expressed concern that design guides focus on a single extreme event during the lifetime of infrastructure, but there is increasing evidence of sequences of multiple events contributing to a larger failure. They would like to understand better what the public health and safety impacts are of multiple rare events and the likelihood of that happening (e.g., McDevitt 2022). They also identified the need for a process to understand the sensitivity of engineering decisions to multiple consecutive events as well as the sensitivity to different projected futures. Concern was also expressed about the potential for compounding events, such as rain on snow, because these can dramatically increase design loads and costs but are not always considered in an appropriate manner.

In establishing how civil engineering practice employs rainfall data, there were also some discussions of higher-end applications (i.e., high risk and impact projects such as dam design). Such projects consider the PMP, but the methods are not prescribed or standardized by ASCE. Workshop attendees identified a need to incorporate new understanding in PMP estimates, particularly with respect to climate change and to address concerns that PMP estimates may still be "too high" (that is, higher than needed for the desired risk level) despite recent exceedances of PMP (e.g., Hurricane Harvey). NOAA attendees reported that the recent Bipartisan Infrastructure Law provides explicit funding for improving PMP science. It is anticipated that recommended strategies to shape a modernized PMP product will be developed over the next two years through the National Academies of Sciences, Engineering and Medicine (NASEM) study with the product(s) developed over the subsequent three years (available at: https://www.nationalacademies.org/our-work/modernizing-probable-maximum-precipitation-estimation). Regardless of the existence of ASCE formal publications (e.g., Standards or MOPs) on the use of PMP, it was also recommended by participants that ASCE formally contribute to the NASEM study. It was felt that discussions on this topic would need to be broadened to include other Federal partners (e.g., United States Army Corps of Engineers (USACE)).

The exploration of how current engineering practices incorporate recently observed changes in extreme rainfall started a discussion about the validity of long records in the context of non-stationarity. For instance, older records help to put changes that we have observed recently into context. Paleoflood data (e.g., derived from tree rings) are also beneficial in introducing design conservatism. It was suggested that maybe older records be weighted in some way to facilitate their use and improve statistical estimates, while still favoring the more conservative approach from using recent observations.

With respect to projected changes in intense coastal rainfall, it was noted that the relationship between intense precipitation and tide is associated with approaching tropical storm systems. Therefore, it can reasonably be assumed that the most intense storms will occur at the same time as high tides. There is a forthcoming MOP from CACC on compound flooding that speaks to this issue.

A participant noted that there needs to be flexibility in approach to accommodate both the small-scale projects that are reliant on a standardized process and the larger-scale, one-off projects. In the first case, designers are often constrained by budgets and time to implement design codes/MOPs in a formulaic manner (e.g., for detention ponds or storm drains) and would benefit from a simple approach to incorporating climate change, such as through a factor of safety or prescribed range of projected values depending on the risk classification of the project. The latter case will demand deeper deliberation and creativity and will likely have the allowable budget to work more closely with climate scientists to examine the range of uncertainties presented by different climate models and projected scenarios.

3.2. NOAA Climate Products, Information, and Approaches

3.2.1. Available NOAA Climate Products and Information

Participants were asked to identify which, if any, NOAA weather and climate products are currently employed in civil engineering practice to characterize rainfall intensity. It was assumed that those in prevailing use are based on historical observations and assume stationarity.

Atlas 14 is very familiar to the ASCE community. NOAA has developed a methodology that will account for climate non-stationarity. Atlas 15 will come in two peer-reviewed volumes, published concurrently (more details at: https://www.weather.gov/owp/hdsc). Volume 1 will replace Atlas 14 (historical data) and provide coverage across the United States and affiliated territories. Volume 2 will incorporate regional adjustment factors to account for climate change. The target completion date for CONUS is 2026 with CONUS (States and Territories outside CONUS) following in 2027. Participants expressed a desire to see Atlas 15 Volume 1 advanced rapidly as there is considerable concern that earlier volumes of the data in Atlas 14 are already 20 years old.

Atlas 14 estimates are point estimates. Spatial patterns and areal distributions of extreme rainfall are not represented in Atlas 14. Participants would like to see this capability supported by NOAA as the information is important for networked designs in larger watersheds.

Engineers are currently accommodating climate change in design either by utilizing a more conservative design storm (e.g., using a 25 year/4 percent annual probability storm rather than the 10 year/10 percent annual probability) or with the use of a scaling factor. Anecdotally, participants referred to different jurisdictions that have adopted both approaches or limiting the use of observational records to only the most recent 40 years to estimate annual probabilities. Participants emphasized the importance of a defensible and well captured approach that is upheld by ASCE, even in the absence of updated data. It was expressed that most engineers would prefer either a single value or a range of high, medium, and low estimates with a justification for the adoption of any of these (e.g., within the code commentary).

3.2.2. Capabilities Ripe for Incorporation to Practice

Participants discussed how the relationship among extreme precipitation, precipitable water, and temperature is well established. Consequently, this is a scientifically justifiable way of bounding projected increases through the use of a simple scaling factor linked to the Clausius-Clapeyron relationship. Caution was expressed with regard to sub-daily precipitation where there may be greater increases in intensity with respect to temperature. Another area of concern was tropical cyclones where the slower propagation of storms may have a compounding effect with resultant higher total volumes of rainfall similar to what was observed during Hurricane Michael. The workshop participants generally agreed that in the absence of better information a scaling relationship based on seven percent increase in extreme rainfall per °C of warming is a good precautionary design approach.

While NOAA NCEI has considerable available observational data, including historic hourly records; many people are unaware of where to access the data. Making these data more readily accessible would be very useful. There was also some discussion about the use of re-forecast and hindcast data in addition to radar and satellite observations to supplement observational records in data sparse areas. The workshop participants did not agree on the best methods for communicating such information for use by generalist engineers.

3.2.3. Nascent Capabilities

Workshop participants identified other research and capabilities that may be developed with time and research to characterize rainfall intensity for use in civil engineering practice. Some of these are below.

Department of Defense resourced NCEI to look at how IDF curves may change in the future as atmospheric water vapor increases. The project combined two major components of change – potential changes in water vapor capacity and potential changes in the meteorological systems that trigger/deliver major rainfall events with downscaled climate model output (Localized Constructed Analogs). This will provide an alternative set of projected rainfall intensities to those coming from Atlas 15. Participants were particularly concerned that a diversity of methods, assumptions, and data should be used to develop the final set of information to be used in codes and standards. However, there was also acknowledgement that the availability of several different data sources can be confusing for users when the differences between outputs are not clear. Some large organizations (such as the Dam Safety and Infrastructure Office at the Bureau of Reclamation) and the science community are comfortable with the use of model ensembles to derive estimates of future projections of hazards. However, there is a need for methods to incorporate the range of estimates into standards in ways that standard developers and users are able to adopt.

NOAA climate modeling is moving to 25 km grid spacing that captures larger rainfall events. They are also pursuing 3 km global grid spacing, which promises significant improvement in capturing the most intense convective type storms.

A recurrent theme from the engineering community was the need for sub-hourly (1 to 15 minute) precipitation for urban stormwater drainage applications. This is beyond the scope and capabilities of current modeling. It is critical for flood mitigation approaches that attempt to slow down water before it reaches the urban flood prone zones, such as highway intersections/sag points; residential and commercial basements; and transportation infrastructure. ASCE standards documents (e.g., ASCE/SEI 7) may not be able to completely capture the newest developments in precipitation information during a particular development cycle. In these cases, ASCE MOPs may be an effective way to facilitate early adopting practitioners' use of emerging precipitation information through presenting best processes and practices.

There was a near-unanimous agreement amongst the workshop participants to avoid committing to selecting specific scenarios (RCP or Shared Socioeconomic Pathway) or even scenario-like approaches (pinning to global temperature). They cited the need for external expertise to examine more complex/uncertain portions of the larger picture (e.g., economists for economic growth and handling regulatory interventions).

4. Workshop II Outcomes: Straight-Line Wind

The goal of these workshops was to identify engineering needs as framed in key climate-sensitive standards and to identify existing or potential climate datasets and products that could meet these needs. The summary that follows reflects the contributions and expertise of the workshop participants but is not intended to be a comprehensive needs or requirements assessment.

4.1. Introduction

Near-surface winds are a key environmental factor to consider in the design of various engineered structures. Physical pressure loading due to winds impacts structural and material durability and performance. Numerous wind-driven design considerations currently exist in ASCE MOPs and standards. A variety of meteorological phenomena drive extreme surface winds of concern for design standards. Examples include tropical cyclones, extratropical cyclones, mesoscale convective systems (thunderstorms or derechos), and terrain forcing. Also, special regions where winds have localized forcing such as mountain regions can drive near-surface turbulence and wind channeling, commonly referred to as “wind speed up effects.”

Winds are influenced by variability and change in the climate system, and there is increasing, but still incomplete, knowledge of the nature of those changes. Global climate model output, in combination with observations and fine- or regional-scale modeling, can be used to estimate wind climatology and change.

A group of wind loading experts from ASCE, various experts in meteorology-influenced engineering design practice from Federal agencies and academic institutions, and Federal and academic experts in meteorological winds and computational modeling of the atmosphere and climate gathered for the workshop. This group discussed the types of considerations that exist in civil engineering practice which are wind sensitive, the state of meteorological analysis in wind-based standards, issues with those standards, the interest in incorporating non-stationary climate change into wind estimates used in the standards, the state of modeling and science around near-surface winds, and the possibilities for developing wind projections to inform non-stationary engineering standards incorporating climate risk.

4.2. Identifying Engineering Needs

4.2.1. Design Standards

ASCE/SEI 7 was the primary focus of discussions. ASCE/SEI 7 helps engineers determine design loads taking into account various environmental hazards, including wind, and ASCE/SEI 7 provisions are relied upon through ASCE MOPs and other industry standards for the development of the hazard considerations used in design.

ASCE/SEI 7 includes sets of composite wind speed maps (such as Figure 4.1) that integrate multiple meteorological sources of risk and produce risk assessments for four building risk categories and multiple wind speed mean recurrence intervals.

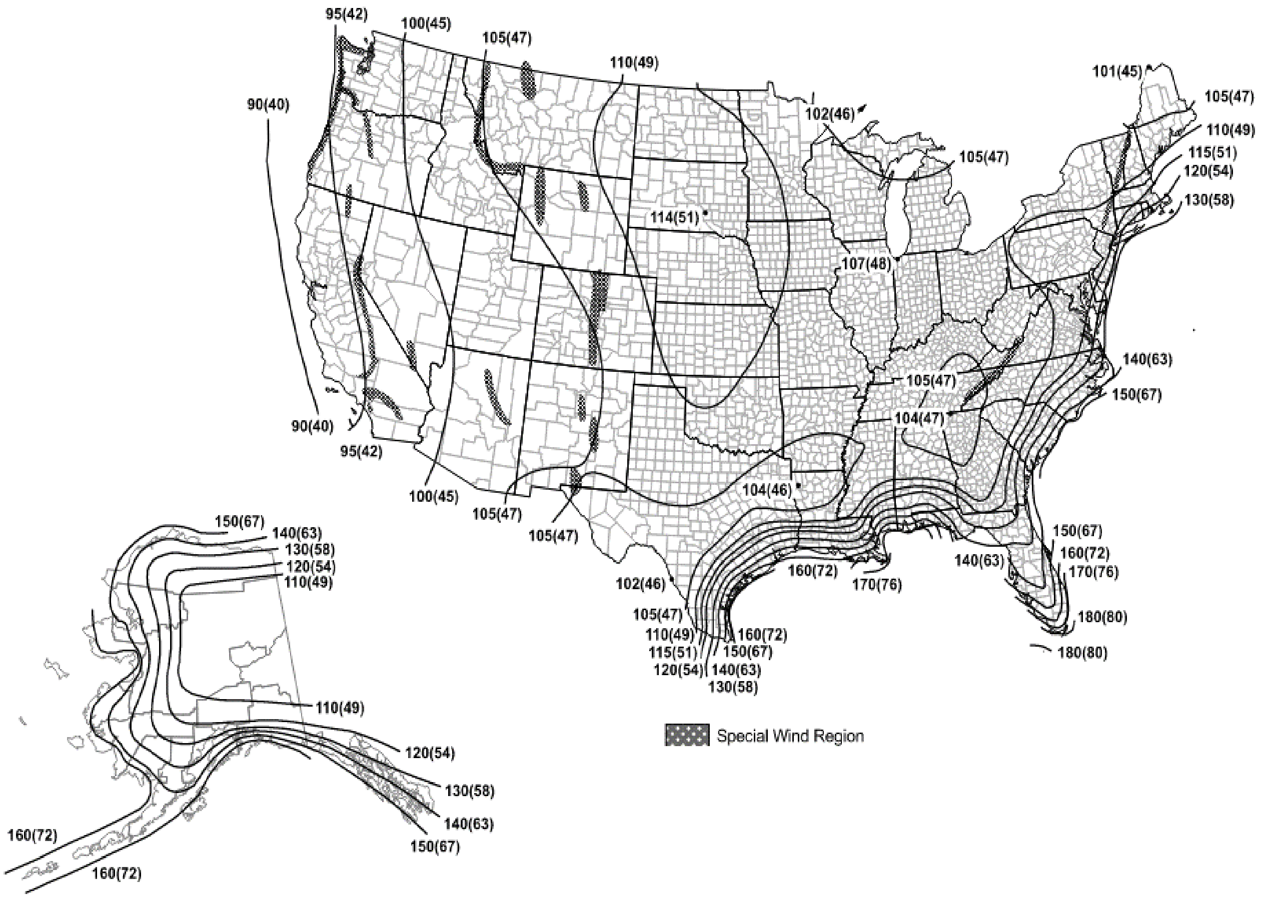


Figure 4.1. A 700-year Wind Speed Risk Category II Map from ASCE/SEI 7-22 for Engineering Consideration Isotachs (lines showing particular values of wind speeds) indicate the expected 700-year wind speed risk in a particular area. The sharp cluster of lines along the Gulf and East coasts is reflective of the impact of tropical cyclone winds along the coastline, and how quickly those impacts decrease as tropical cyclones diminish over land.

The four risk categories differentiate structures according to performance expectations and the risks associated with failure. The risk categories are as follows:

- Category I: uninhabited structures such as barns where failure would likely not result in mortality.
- Category II: common structures such as homes where loss of life associated with structural failure would be constrained to a small number of people and where failure of an individual property does not have cascading effects on other structures.
- Category III: congregant structures where building failure would impact significant numbers of people. This category may include schools and theaters.
- Category IV: essential structures that are needed to support the community through a disaster and cannot experience structural failure under design level events. Examples include hospitals, fire stations, police stations, or penitentiaries.

Current wind-oriented standards use historical observed data from surface meteorological stations that directly record wind speeds. The analysis that leads into map development disaggregates the various meteorological sources of wind variability at a particular location. In other words, separate analyses are done for mesoscale storms, extratropical cyclones, and other wind drivers. Tropical cyclone hazards, because of their infrequent nature, are modeled to evaluate the distribution of wind speeds from various storms and locations along the hurricane-impacted coastline of the United States. Those analyses are then integrated into a single map for inclusion in ASCE/SEI 7. Because of limitations in the historical extent of wind observations, statistical models are used to interpolate and extrapolate wind observations to a full probability distribution that can be used to evaluate the types of extreme wind conditions of most interest to engineers.

4.2.2. Key Physical Variables for Wind Impacts on Structures

A number of variables and coefficients are used in the calculation of wind loading, see for example Equations 4-1 and 4-2 as follows:

$$q = 0.000256\, KZ\, KZt\, Ke\, V^2 \qquad (4\text{-}1)$$

where q = pressure forcing, 0.000256 = density of air accounting for temperature and storm type, KZ = exposure coefficient, KZt = terrain coefficient, Ke = elevation factor, and V = basic wind speed in miles per hour.

$$p = q\, Kd\, G\, Cp - qi\, Kd\, (GCpi) \qquad (4\text{-}2)$$

where p = wind pressure on building component, Kd = directionality factor, G = gust factor, Cp = external pressure coefficient, qi = pressure forcing at location i, and ($GCpi$) = internal pressure coefficient at location i.

The most important of these variables is the three second gust wind speed measured at ten meters in elevation off the surrounding grade. Wind speed is the most important variable and sensitive to even small climate change-driven shifts, because wind speed is squared to arrive at an estimate of pressure forcing so the climate shifts are amplified when converted into pressure forcing by the squaring. Wind speeds are likely changing in response to shifts and differences in the strength of various meteorological phenomena and are of primary interest for ASCE/SEI 7 updates in treating non-stationarity.

Another key variable in calculating pressure forces due to wind is the surface roughness length upwind of the site, which measures near-structure wind exposure and also contains information determinative of local turbulence. Roughness length is influenced by the nature of ground cover in a nearby area, whether there are other structures, trees, topography, or other surface cover that alters the flow of the wind in a given area.

Roughness length also has a particular effect given the direction of the wind in circumstances where the nearby land cover is heterogeneous over a range of directions from the location of interest (i.e., if there is flat uncovered land in one direction, which allows significant unimpeded wind fetch, versus forested area in another direction, which impedes wind flow). Roughness length is changing over time both through human alteration of the land surface (e.g., deforestation or development) as well as climate change impacts (e.g., vegetation greening due to carbon dioxide fertilization altering growth patterns). A large-scale slowing of terrestrial winds has been observed over the past three decades and is commonly, although not decisively, attributed to land surface changes.

Finally, air density is another key atmospheric variable that influences pressure forcing based on the amount of atmospheric mass being driven against an engineered surface because higher-density air imparts more force at a given wind speed. Air density is also likely changing as the climate changes under the influence of the general warming of the lower atmosphere over land (which decreases near-surface density) as well as potential increased variability in local air temperature over days, weeks, and months. Some density-sensitive activities, such as airplane takeoffs and landings, have been observed and are incurring engineering considerations to respond to these density changes (e.g., lengthening runways). In the long term, ASCE is interested in evaluating the effects of changing air density, but this will require extended evaluation to consider non-stationarity in the density term for wind loading calculations.

4.2.3. Temporal and Spatial Scale Considerations

Temporal and spatial scale considerations in engineering practice were considered and mapped to climate change timescales and modeling and geophysical data. There are a number of temporal and spatial scale considerations associated with wind forcing. Temporal scales considerations include the high-frequency, short-duration gust forcing on structures, the return period consideration which communicates how often a particular extreme wind speed would be expected to occur at a given location, and the design lifetime expectations for a given structure. All of these temporal considerations engender specific practice-to-practice challenges needing consideration by the engineering and meteorological communities.

As noted above, the primary variable of interest is three-second gust wind speeds. This is a very high-frequency data requirement from a meteorological perspective and includes temporal meteorological variability down to the turbulent scale. The engineering community has developed ways to interpolate three-second wind gust information from other gust or averaging periods that may be taken over longer timescales (e.g., one minute, three minute, or hourly average wind speeds) as opposed to those more commonly available from observed (see Figure 4.2) and modeled data produced by the meteorological community.

Each structural risk category, as described in Section 4.2.1, considers a different extreme wind return period (Table 4.1). Longer return periods, corresponding to more extreme wind speeds, are used in the design of structures with a lower risk tolerance. Risk Category IV structures (e.g., hospitals and penitentiaries) use 3,000 years as their design wind speed MRI. This essentially isolates the strongest three-second wind speed gust that would be expected in a 3,000-year period. These long return periods are clearly an analytical challenge when, at best, the meteorological community may have recorded only around a century of observed wind speed data. Climate models can be useful in this respect, as some model experiments have generated tens of thousands of years of data, which provides a fuller sampling of hypothetical natural variability. A 3,000-year return period is typically interpreted as a 1/3000 probability of exceedance in any given year. The use of exceedance probability is recommended under conditions of climatic non-stationarity.

Regarding spatial scale in current engineering practice, ASCE maps such as that in Figure 4.1 show continuous wind isopleths that are a spatially smoothed representation of the extreme wind speed climatology. On the meteorology side, wind speed observations (from which such maps are derived) are collected in a heterogeneous manner, depending on the location of particular measurement stations, which creates significant spatial gaps in measurements that may overlook mesoscale variability.

The representation of various atmospheric phenomena within climate models is dependent on the spatial resolution of the model. In turn, available computational resources often limit the spatial resolution at which climate models can be run. Most contemporary global climate models are run at 50-to-100 km grid resolution or equivalent (it takes approximately 3,200 50 by 50 km grid cells to cover the CONUS). Regional (limited-area) models are typically 10-to-50-km resolution, while high-resolution "convection permitting" atmospheric models are finer than 4 km resolution. Additional classes of models (e.g., Large Eddy Simulators) can target smaller spatial scales on the order of tens or hundreds of meters and can resolve many aspects of turbulent motions in the boundary layer near the Earth's surface. All of these models are potentially of use in wind speed estimation applications, and combinations of different model outputs can be useful to simulate different phenomena. Tropical and extratropical cyclones typically require at least 25 to 50 km atmospheric model resolution to be well-simulated. Faithful simulation of mesoscale phenomena, such as thunderstorms, requires even higher resolution.

Table 4.1. ASCE/SEI 7 Structural Risk Categories and Their Associated Return-Interval Risk

Risk Category	Target Beta (Chapter 1 in ASCE/SEI 7)	ASCE/SEI 7-10 Map MRI (years)	ASCE/SEI 7-16 Map MRI (years)
I	2.50	300	300
II	3.00	700	700
III	3.25	1,700	1,700
IV	3.50	1,700	3,000

Note: The third column contains values from the 2010 edition of ASCE/SEI 7 and fourth column from the 2016 and 2022 updates.

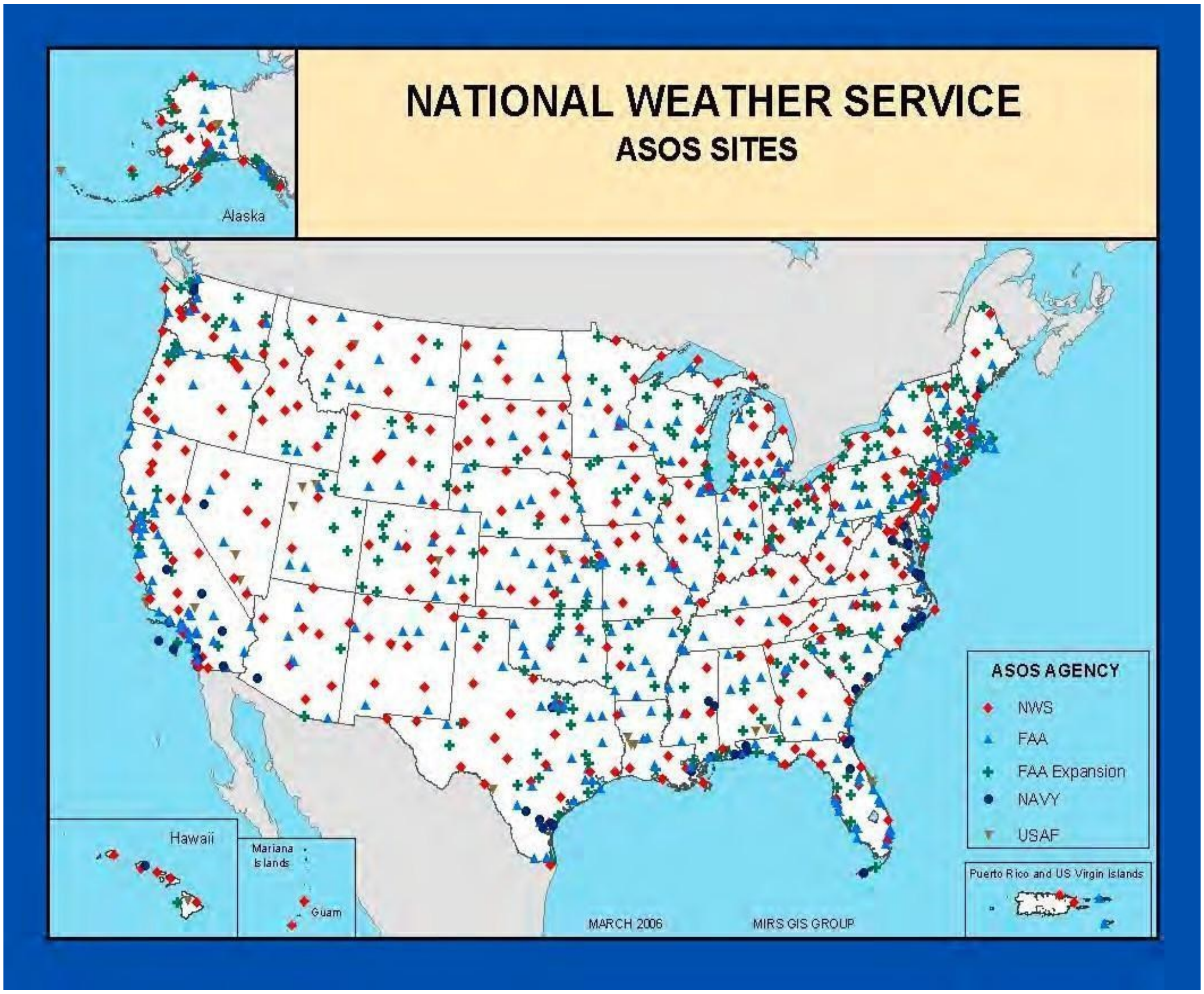


Figure 4.2. Map of Automated Surface Observing Station (ASOS) Sites Operated by Various Agencies These stations all collect near-surface wind speed measurements and have varying lengths of record.

4.2.4. Uncertainty in Engineering Use of Wind Speed Data, Measurements, and Modeling

Wind speed, as an input to wind loading calculations, is highly sensitive to uncertainty given the squaring of the wind speed term in the pressure forcing calculation. For example, a 700-year return wind speed along much of the Southeastern United States coastline is approximately 150 miles per hour. If the error on that estimate is 10 percent, the corresponding pressure forcing error is at least 21 percent. Existing wind speed estimates used to derive ASCE/SEI 7 risk maps are already subject to uncertainties and gaps in observations as well as statistical assumptions used to interpolate the full probability distribution of extreme wind speeds. Integrating model data and approaches into wind load estimations may improve data gaps and associated uncertainty issues in estimates of wind-induced pressure loading under current conditions. The same methods may then be leveraged for future climate scenarios.

There are challenges associated with selecting future climate scenarios given the uncertainty of emissions forcing, which grows as projection timeframes get longer. A variety of future climate scenarios are available that derive from a range of assumed policy outcomes. In order of greatest to least mitigation of climate emissions and resulting impacts, these are: rapid adoption of net zero or even net greenhouse gas drawdown policies, ambitious implementation of current greenhouse gas reduction commitments under international agreements, implementation of current enacted policies under international agreements, policies that would see continued development according to recent policies, and continued unabated expansion of fossil fuel use and GHG and aerosol production. The policy range is less important when considering time frames of 10 to 30 years into the future where climate impacts are more dependent on the climate change coming from past actions. Policy becomes a much larger source of uncertainty beyond 30 years, where the range of future emissions and forcing on the climate system is larger (see Figure 4.3). For engineering practice, some participants suggested that choosing an emissions scenario compatible with current or enacted global policies could balance the desire to sample a range of forced climate impacts with the pragmatic approach of median-based engineering practitioners.

Roughness length uncertainty around wind measurement stations is a significant issue that has provoked detailed analysis of the environmental conditions around measurement stations. Practitioners in the development of wind speed information for engineering practice have undertaken a process of examining directional roughness length heterogeneity around measurement stations to develop directionally dependent corrections for wind measurements at the observational stations used to estimate local wind variability.

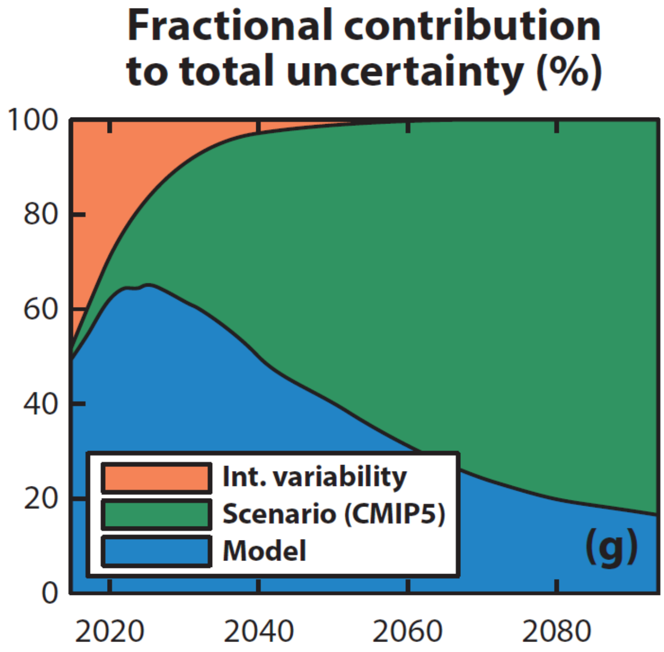


Figure 4.3. Estimates of the Relative Size of Three Sources of Future Uncertainty in Climate Projections Uncertainty may come from internal variability (the natural variations of the climate system on particular timescales), scenario uncertainty (the forcing from GHG and aerosols), and model uncertainty (the aspects of the climate system that are poorly understood and simulated). The graph starts in 2015 and runs to 2100. At 10 to 30 years in the future, scenario uncertainty accounts for 15 to 30 percent of total uncertainty.

4.3. ASCE/SEI 7-28 Schedule Considerations and Potential Near-Term Approaches

The next update of ASCE/SEI 7 is scheduled for publication in 2028 (referred to as ASCE/SEI 7-28). According to estimates of the revision timetable at the time of the workshop, to be incorporated into ASCE/SEI 7-28, the Committee would need input by the first quarter of 2025 on significant revisions, such as the inclusion of non-stationarity of wind speeds. This allows approximately two years as of the writing of this report for meaningful work and improvements in advance of this update.

The nature of the ASCE/SEI 7-28 wind map update is not completely established. Two possible approaches to the inclusion of non-stationarity were discussed at the workshop. Non-stationarity may be considered by producing a scaling factor map to enable inclusion of additional climate risk or by producing updated risk maps inclusive of non-stationarity. The former approach could allow engineers some degree of freedom to include climate non-stationarity multipliers according to their risk tolerance and customer disposition. The latter would automatically include some degree of non-stationarity risk for all engineering considerations. Scaling factors could vary based on the structural risk category. For example, design of a risk-intolerant structure may use a more significant climate risk multiplier whereas design of a lower risk structure may either not consider additional climate risk or use a lower multiplier. In addition, the choice of scaling factor could vary depending on design life considerations for a particular structure.

4.4. Other Applications of Wind Speed Data

In general, the use cases for wind speed and loading information are clear. However, there are several non-ASCE/SEI 7 standards that rely on ASCE/SEI 7 wind provisions and extra-ASCE contexts in which wind speed and loading information is used. The following list provides examples of non-ASCE/SEI 7 standards:

- American Forest & Paper Association (AF&PA)/ASCE 16-95: *Standard for Load and Resistance Factor Design (LRFD) for Engineered Wood Construction*
- ANSI/ASCE 3-91 *Standard for the Structural Design of Composite Slabs* and ANSI/ASCE 9-91 *Standard Practice for Construction and Inspection of Composite Slabs*
- ANSI/ASCE/Transportation & Development Institute (T&DI) 21-13: *Automated People Mover Standards*
- ASCE 17-96: *Air-Supported Structures*
- ASCE 20-96: *Standard Guidelines for the Design and Installation of Pile Foundations*
- ASCE/Coasts, Oceans, Ports, and Rivers Institute (COPRI) 61-14: *Seismic Design of Piers and Wharves*
- ASCE/EWRI 42-04: *Standard Practice for the Design and Operation of Precipitation Enhancement Projects*
- ASCE/SEI 19-10: *Structural Applications of Steel Cables for Buildings*
- ASCE/SEI 37-14: *Design Loads on Structures During Construction*
- ASCE/SEI 48-11: *Design of Steel Transmission Pole Structures*
- ASCE/SEI 52-10: *Design of Fiberglass-Reinforced Plastic (FRP) Stacks*

- ASCE/SEI 8-02: *Specification for the Design of Cold-Formed Stainless Steel Structural Members*

The following list provides examples of additional ASCE needs and associated contexts:

- 1,000,000-year return-period maps of wind risk by the Nuclear Regulatory Commission
- 10,000-year return-period maps used for Liquid Natural Gas applications and promulgated by the Federal Energy Regulatory Commission
- The ICC-500 storm shelter standard and design for FEMA safe rooms and shelters, which use 10,000-year hurricane maps

4.5. State of Wind Speed Data and Understanding of Climate Change Impacts

Current wind speed estimates are based on ground-based measurement stations that have multiple decades of historical wind speed data for non-tropical storms. Wind speed probability distributions are extrapolated from these measurements with appropriate statistical distributions. Because of the detail of these measurements and the frequent sampling of relevant meteorological phenomena (e.g., extratropical cyclones typically pass over most mid-latitude measurement stations once every five to ten days), probability distributions can be reasonably estimated outside of tornado and tropical cyclone regimes.

There is more emerging work in the area of phenomenon-discriminated wind speed estimation, where wind risk associated with particular meteorological phenomena (e.g., tropical cyclones or extratropical cyclones) is estimated separately for each phenomenon and then later combined into a single wind speed map.

Tropical cyclones, particularly landfalling ones, are significantly less frequent phenomena, and statistical methods are required to estimate wind speed probability distributions based on general storm risk. Models have varying degrees of ability to incorporate climate change boundary conditions and an appropriate intensity distribution for tropical cyclones. That said, some state-of-the-art coupled global models have demonstrated good distributional statistics when horizontal atmospheric resolution approaches the 25 to 50 km range. As a result, an ecosystem of statistical-dynamical tropical cyclone models has been developed to tackle this challenge. Some initial work has been undertaken to apply different tropical cyclone risk models to generating wind speed distribution information for tropical cyclone wind regimes. One such collaboration, between Applied Research Associates (ARA), NCAR, Massachusetts Institute of Technology (MIT), and GFDL has generated wind speed distributions. There are a number of other tropical cyclone risk modeling activities in the research community that could be relevant, including the Columbia University Tropical Cyclone Hazard Model or CHAZ, Nadia Bloemendaal’s Synthetic Tropical cyclOne geneRation Model or STORM model, and Ning Lin’s Princeton environment-dependent probabilistic tropical cyclone model or PepC model.

Some work on extratropical cyclones is ongoing, looking at simulating cyclone risk in future environments. This involves collaborations between NOAA, National Science Foundation, and

NIST. Extratropical cyclones are generally well-simulated by models, although details and rapid changes in cyclone strength are better represented in higher-resolution models.

Mesoscale convective systems such as thunderstorms have received some nascent attention. These have largely been through the application of extreme value theory to underlying environmental signals given the spatial resolution limitations of existing observational and modeling data to explicitly resolve mesoscale system strength and frequency.

Tornado climatologies have been studied to understand frequency, intensity, and location of tornadic thunderstorms and associated winds. Some understanding of climate impacts on tornadoes is emerging. However, much more work needs to be done to resolve non-stationarity. Tornadoes are not sampled by observing systems and are not explicitly simulated by existing common atmospheric models.

A significant amount of work has been done to understand phenomenological uncertainty. Some methods applied to handle this uncertainty include Monte Carlo modeling and the application of extreme value theory to help estimate low-frequency high wind events. In general, the degree of uncertainty for tropical cyclones is assessed to be medium, medium to high for extratropical cyclones, and high for mesoscale systems.

There are a number of best practices that should be observed in pursuing further work on wind risk, particularly when integrating non-stationarity signals derived from climate models. One best practice is to consider a number of climate-forcing scenarios that envision different levels of GHG forcing in the future; this helps capture a robust range of nonlinear changes that may occur in wind regimes. Instead of considering wind changes at a future date, ASCE may instead use an impacts-by-degrees approach (also referred to as a "Global Warming Level" approach). This would mean selecting a hypothetical future amount of climate change compared to pre-industrial conditions (e.g., three °C, a level well-supported by current estimates of future energy systems emissions) and the accompanying change in winds at that temperature change level. The advantage of this approach is that it somewhat eliminates the need to grapple with emissions scenarios decisions and integrates useful information about different impacts caused by fast versus slow climate approaches to a particular degree change.

Multiple models must be used to provide wind speed estimates and estimates of future change in wind speed regimes. There are significant differences in model-to-model formulation that result in different wind climates and responses to climate forcing. In addition, modeling systems across different scales should be considered including relatively high resolution (i.e., small grid sizes) global, regional, and atmosphere-only as well as explicit turbulence approaches. At the global scale, there is a wealth of information in the Coupled Model Intercomparison Project (CMIP) experiments to use, including regional-scale runs of global models through High Resolution Model Intercomparison Project. GFDL has developed capabilities in its atmospheric models to perform "stretched-grid" experiments where more grid cells (and thus higher resolution) may be applied to areas of interest. Coupling these models with ocean models to create a true climate model simulation has not yet been done because of resource limitations. However, it is on the medium-term horizon. There are a variety of relevant regional modeling activities at NCAR and Department of Energy that would be highly relevant to wind analysis, including the Coordinated

Regional Climate Downscaling Experiment and HyperFACETS, where regional-scale climate projection and impacts information is tested and developed for applied uses. It may be possible to blend various modeling and observational data, and/or to use high-resolution atmospheric models to correct coarse regional or global climate models. Examples include the NOAA High Resolution Rapid Refresh hindcasts, which have already been used in wind energy applications, or limited Large Eddy Simulations. A blending of cross-scale modeling approaches would enable robust analytical approaches and better-informed, phenomenon-centered wind speed change estimates.

Large ensemble climate models should also be used. In general, climate projection experiments such as CMIP include a large number of climate model ensembles that can help define phenomenological variability and provide estimates of long return period behavior. There are also individual model large ensemble experiments, such as those done at NCAR with the Community Earth System Model, or those done at NOAA GFDL with the SPEAR system, which can similarly provide many years of data with which variability can be sampled. NOAA's SPEAR system currently has projection data available for wind speed at 50 km resolution under climate forcing scenarios. SPEAR has produced development-grade 25 km datasets that are undergoing quality control and may be available over the next few years.

A number of statistical approaches used to define wind probability distributions should also be considered. A number of examples of approaches in the tropical cyclone space were given earlier. Additional approaches for extreme value estimates in the realm of mesoscale cyclones could be tested.

4.6. Activities within the Next ASCE/SEI 7 Update Cycle

Given the immediate ASCE/SEI 7 update schedule for the next edition, the practical usable window for updates is early 2025.

For the analysis of winds driven by extratropical cyclones, there is likely some analysis that could be performed within this timeframe based on existing simulations and within ongoing or potential new projects. Analyses could leverage the relatively good-quality existing climate model data, such as Coupled Model Intercomparison Project Phase 6 (CMIP6) simulations. There is some pre-existing analysis of and literature about extratropical cyclones in CMIP6 simulations on which to base new analysis. Work could potentially examine low probability events in high- and low-resolution simulations to begin to understand resolution dependencies and model fidelity to observed estimates of wind speed distributions in extratropical cyclones. Analysis approaches might consider working at storm scale, which would generalize wind speed estimates somewhat toward the meteorological phenomenon instead of to a particular location.

For winds driven by thunderstorms, there are a variety of potential activities that could supplement or complement ongoing activities. For example, higher resolution simulations (e.g., High-Resolution Rapid Refresh (HRRR) at 3 km where HRRR is driven by radar data that samples thunderstorms in real time) could be used to bias correct GCM output. Machine learning approaches could be applied to translate between the training data and GCM output. A similar strategy could also be used in applying Large Eddy Simulation output to GCM bias correction.

Given that much of the ongoing, directly applicable tropical cyclone work is taking place outside of NOAA, it is not clear what NOAA capabilities could be rapidly developed in a two-year timeframe. Collaborations with the existing communities could potentially be fruitful. It would be worth exploring whether the application of high-resolution SPEAR experiments to this problem could be accomplished in the next couple years. Some of the external work, such as the ARA/MIT collaboration, is possibly going to yield useful results in time for the immediate ASCE/SEI 7 update cycle.

For tornadoes, there is a need for further research on climate forcing of tornadic thunderstorms to improve the baseline understanding of how the associated wind fields will change and shift over the next few decades. There is not a clear activity that could be done in the two-year update timeframe for ASCE/SEI 7 that would result in improved tornado-related wind risk estimates.

A significant consideration in determining the feasibility of near-term work is the availability of funding or ongoing projects that can be leveraged. There are some relevant proposals expected in response to the NOAA/OAR/CPO Modeling, Analysis, Predictions, and Projections program fiscal year 2023 solicitation that may help advance a number of the areas above. These projects would likely start in late summer 2023 and thus would have a limited window within which to impact ASCE/SEI 7 updates. NOAA could explore whether internal non-competitive collaborations may be feasible to address some of the areas above given the highly relevant work taking place across many parts of the agency. These collaborations may be faster to fund and initiate given internal resource transfer protocols and the potential alignment and interest of NOAA researchers who work in a number of the above areas or with a number of the above-mentioned tools.

4.7. Impediments to Producing Forward-Looking Design Wind

4.7.1. Resource consolidation and organization

The observational and modeling data as well as expertise needed to work on the climate-related aspects of this problem are widely distributed across Federal agencies, modeling centers, and the academic and private sector communities. For data, NOAA should consider consolidating and making available its own data and assisting in the consolidation of additional relevant datasets through partnership with relevant non-NOAA groups (e.g., NCAR). Interagency partnership and collaboration are important here and may be accomplished through groups such as ICAMS and USGCRP.

4.7.2. Process fidelity at useful scales

In the modeling realm, the community has made meaningful advances toward higher resolution over the past decade and is now approaching model resolution scales that can meaningfully represent the types of phenomena of interest to forward-looking design wind application. However, global models used to simulate climate impacts are still run at resolutions that fail to fully and faithfully represent particular phenomena explicitly (e.g., mesoscale systems) or impacts of other phenomena (e.g., rapid development of extratropical cyclones or the specifics of their wind fields near the surface). This reality means that more complicated analysis techniques need to be incorporated, which can introduce complexity, cost, and the potential for more degrees of uncertainty in some cases. There is no one current model or dataset that can produce all of the needed input to ASCE/SEI 7 engineering standards for all wind related phenomena.

4.7.3. Ambiguity in Uncertainty

A final surface wind analysis contains many sources of uncertainty. Adding non-stationarity increases the sources of uncertainty in a number of ways, including time frame selection versus impacts-by-degrees; scenario uncertainty; model uncertainty; etc. The tolerance for these additional degrees of uncertainty in the engineering community and the best way to navigate this are unclear. Some tolerance issues may be avoided through effective and simple communication of the end product and the processes involved in producing it.

4.7.4. Handoff confusion

In some respects, the clearest elements of the practice-to-practice relationship exist within the practices, engineering practice identifying the needs and climate science practice identifying the analysis pathways. The handoff between the two practice communities is where some confusion may arise and where much care must be taken. For example, questions around the form of information transfer include if a dataset, tool, map, or other resource is needed. Other sample questions are below.

- How do we tackle translation issues between communities that use different types of data formats, coding languages, and analysis software?
- Does the climate community have the capabilities and resources to produce a particular kind of product?
- Does the engineering community have the bandwidth and resources to update this product and integrate it into design standards?
- How do we not overwhelm the engineering community with uncertainty considerations common in the climate science community?

4.7.5. Resources

On the climate side, the activities described above have a high degree of funding program relevance and thus a strong prospect for research and development support because of the involvement of significant modeling research and development questions. However, competitive resources are unreliable and subject to unpredictable and months-long competitive review processes and potential project failure in the review process. On the engineering side, there is a lack of resources for analysis and additional modeling and statistical steps needed in some cases to turn climate data into engineering-ready products.

4.7.6. Timeline

The update schedule of ASCE/SEI 7-28 is aggressive in light of the considerable research and development and analysis work needed in a number of areas described in this report. For the current cycle, the leveraging of existing or near-term funds and ongoing activities to tackle updates where possible is an advisable approach.

5. Workshop II Outcomes: Coastal Hazards

The goal of these workshops was to identify engineering needs as framed in key climate-sensitive standards and to identify existing or potential climate datasets and products that could meet these needs. The summary that follows reflects the particular contributions and expertise of the workshop participants but is not intended to be a comprehensive needs or requirements assessment.

5.1. Identification of Civil Engineering Needs

5.1.1. Introduction

To prepare for the workshop, the conveners decided to focus on coastal hazards, particularly flooding. They determined that the standard of reference is ASCE/SEI 7-22 because ASCE/SEI 24 directly refers to ASCE/SEI 7 for all flood load calculations (see Table 5.1). All calculations for loads can be reduced to algebraic calculations based on flood depth (i.e., ds= BFE-G, where BFE = base flood elevation, and G = ground elevation, and a single MRI = 100 years is considered). The flood depth depends on multiple variables, but the individual values are not relevant for engineering calculations for flood loads. The ASCE/SEI 7-22: *Flood Supplement* provides a more advanced description of flood-related variables, replacing the flood depth, ds, as the primary climatological variable with the design stillwater flood depth (df) = (SWELMRI-Ge)-ΔSLR, where SWELMRI denotes the stillwater elevation corresponding to the risk category with given MRI, Ge is the elevation of grade at the building or other structure inclusive of effects of erosion, and ΔSLR represents the relative sea level change for coastal sites.

The ASCE/SEI 7-22: *Flood Supplement* recognizes the need for higher MRI to be used to calculate the df for different risk categories structures (i.e., MRI = 100, 500, 750, and 1,000 years for structure categories I, II, II, and IV, respectively as shown in Table 5.2). In addition, the ASCE/SEI 7-22: *Flood Supplement* suggests calculation of loads through explicit consideration of wave heights and flood velocities obtained from maps or local hazard studies, whenever available.

Table 5.1. ASCE Standards Making Reference to Flood

No.	Complete Reference	Title	Flood Related Variables Referenced in the Standard
7	ASCE/SEI 7-22	Minimum Design Loads for Buildings and Other Structures	ds = depth of flood (ds) based on the base flood elevation (BFE) at 100 years MRI and ground elevation
24	ASCE/SEI 24	Flood Resistant Design and Construction	Contains prescriptive requirements and refers to ASCE/SEI 7 for loads

No.	Complete Reference	Title	Flood Related Variables Referenced in the Standard
7-22	ASCE/SEI 7-22 Flood supplement		df with 100, 500, 750, and 1,000 years MRI for different risk categories (when maps are missing, obtained by using a multiplier depending on region and MRI)

Table 5.2. ASCE/SEI 7-22 Flood Supplement MRI and Corresponding Amplification Factors CMRI When Maps Not Available

Risk Category	MRI (years)	Annual Exceedance Probability (percent)	Flood Scale Factor CMRI (Gulf of Mexico)	Flood Scale CMRI (Other)	Flood Scale CMRI (Great Lakes)	Flood Scale CMRI (Riverine)
I	100	1.00	1.00	1.00	1.00	1.00
II	500	0.20	1.35	1.25	1.15	1.35
III	750	0.13	1.45	1.35	1.20	1.45
IV	1,000	0.1	1.50	1.50	1.25	1.50

C_{MRI} = Flood scale factor for mean recurrence interval (MRI)

5.1.2. Geophysical Parameters

The following geophysical parameters/modeling components were identified during the breakout. There is a need to account for climate change in all of these parameters and then aggregate their results for use in the ASCE standards.

- Cyclonic storms/Nor’easters
- Rainfall
- Relative sea level rise
- Great Lakes water levels
- Pacific wave climate
- Ice cover
- Fringing reefs in the Pacific and Caribbean islands

Tsunamis are noted as an important factor when quantifying coastal flood risk within the Pacific. However, the risk of tsunami generation or impacts due to climate change, aside from the effects of sea level rise, are not expected to change.

5.1.3. Temporal and Spatial Scales

The current temporal scale in ASCE/SEI 7-22 is 100-year MRI. The Flood Supplement introduced 500, 750, and 1,000 MRI for risk categories II, III, and IV. The spatial scale is, in practice, determined by the FEMA maps. These temporal and spatial scales may not be appropriate for other applications, such as land use and/or evacuation.

Current temporal scale in ASCE/SEI 24 varies with Flood Design Class (similar to ASCE/SEI 7 Risk Category). ASCE/SEI 24 requires building floor elevation to the 100-year MRI elevation plus freeboard or to 500-year MRI for certain buildings. For freeboard-based cases, temporal scale would have to be determined at a specific site.

Each of the identified geophysical parameters may have different temporal/spatial scales and presents a different level of uncertainty and understanding.

Each parameter has a different sensitivity to uncertainty and the corresponding model capabilities have different maturity levels. However, the selection of a specific climate scenario or of a target temperature increase seems to be the most sensitive issue because both climate researchers and engineers feel poorly equipped to decide. It is likely that different scenarios/temperature increases will need to be selected based on the risk category of the structure under consideration.

5.2. Use Cases and Potential Implementation Opportunities

Different products are under development for some of the identified geophysical parameters. Participants felt that rainfall (NOAA Atlas 15) and relative SLR (Interagency SLR report) are at a good point to be implemented (Sweet, et al. 2022). Others are being developed but only for some regions (e.g., Pacific wave climate and fringing reefs from United States Geological Survey (USGS)). Modeling and understanding of other parameters are only at the level of foundational research and will require a significant effort to achieve the applied research level and then implementation. There is a need for a community of practice that can translate the engineering needs for climate scientists and can describe the scientific limitations of what can be provided to the engineering community.

Another crucial issue is how to combine everything into a single usable product (i.e., map of ds or df for different MRIs). The National Flood Insurance Program or NFIP of FEMA is central, but other products are being developed by USGS, NOAA, National Aeronautics and Space Administration (NASA), etc. A solution could be a partnership between the science agencies to develop products familiar to users/engineers, such as ongoing efforts within USGCRP, the Interagency Sea Level Rise Task Force, and efforts to implement the Federal Flood Risk Management Standard.

Wave conditions are characterized at various locations for CMIP5 and CMIP6 models (such as Erikson, et al. 2016, Storlazzi, et al. 2015, and Erikson, et al. 2022). Also, information is available on storm surge at many geographic locations (see Muis, et al. 2022). Total water levels (downscaled) are available for the entire West coast (Shope, et al. 2022).

The following issues were identified as important but beyond the scope of the breakout session:

- Estimating risk for coastal communities, for example evacuation routes. These need water levels.
- How to communicate risk, including future coastal flood risk.
- Perhaps need to develop policies or standards that more broadly address risk than do ASCE/SEI 7 and 24.

- Compound hazards of flooding and wind.
- Coastal shallow groundwater and connection and responses to SLR.
- Structure scale wave modeling.
- Coastal asset management (temperature and humidity on corrosion, etc.).
- Water intrusion from SLR for foundation systems. Water table level and intrusion of salt water to damage concrete foundations.
- Cities facing lower water tables and drying/rotting wood pilings. Increasing drought threatens this and will be critical in the future.
- Water sources in coastal areas, affecting drinking water.

5.3. NOAA Climate Products/Information

Several capabilities (approaches and products) were identified that are currently employed in civil engineering practice to characterize coastal hazards based on historical observations, i.e., assuming stationarity.

5.3.1. Sea Level Rise

SLR projections are taken from Federal sources. Sweet et al. (2022) published an interagency SLR report (and associated data. Digital access to these projections is available online, primarily through NOAA and NASA web portals. Short summary of these resources is noted here: https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-data.html. Continued dialogue with practitioners about refinements in how these data are presented and made available would likely help the engineering community strengthen these resources even further.

5.3.2. Mean Recurrence Interval Flood Depths

Depth of flooding for a given design flood event is either: (a) taken from FEMA's Flood Insurance Studies or (b) determined through a site-specific analysis performed by the practitioner or available from USACE studies in the area.

Additional capabilities currently exist or could be rapidly developed to characterize coastal hazards at future time horizons with non-stationarity of value to civil engineering practice. The practitioner's need is to be provided future probability distributions for the various parameters that define coastal hazard risk. At a first approximation, this would include SLR, pacific wave climate, and cyclonic storms, which would ideally be provided in the same format as the present-day data is currently provided.

NOAA is currently teaming with FEMA and Department of Defense to define extreme water level recurrence intervals for CONUS, inclusive of future looking statistics under different SLR scenarios. This work aims to use extreme value distributions for various return intervals ranging from 0.1-year (that is, 10 events per year on average) to 100 or more year return intervals. Some participants suggested ASCE/NOAA approach that team, describe ASCE/NOAA's goals, and explore how that planned work product might meet the needs arising from these ASCE/NOAA discussions.

For those use cases for which an existing capability does not currently exist to characterize coastal hazards at future time horizons with non-stationarity of value to civil engineering practice, the team could summarize any approaches explored with any key limiting factors identified.

5.3.3. Pacific Wave Climate

Acknowledging that coastal flood risk within the Pacific is largely driven by wave runup and overtopping rather than storm surge, understanding how the wave climate in the Pacific Ocean will change over time is an important consideration. There is no extant source of quantitative data on how the Pacific wave climate is expected to evolve due to climate change.

Across USGS and NOAA there are efforts underway to perform multi-decadal hindcasts of Pacific wave climate. As noted elsewhere, the workshop participants encouraged NOAA to help via convening multiple Federal efforts and facilitating the movement of research findings into products to services.

5.3.4. Cyclonic Storms

Current “best available” are narrative interpretations of the state of the science. It is an open question as to whether or not the state of the science supports more quantitative projections.

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Appendix A. ASCE-NOAA Task Force on Climate Resilience in Engineering Practice

The Task Force for Climate Resilience in Engineering Practice was established in 2021 to facilitate the collaboration between the ASCE and NOAA in accordance with a cooperative agreement executed between the CTSM of the UMD and NOAA, and a letter of support executed by ASCE to UMD-CTSM for this collaboration. Central to effective design and implementation of this collaboration is engaging UMD-CTSM as a boundary organization for the proposed collaboration as the credible and reliable representation of both the end user community as well as the information provider. Such an approach ensures that any bridging activities envisioned are well designed and targeted.

The Task Force consists of individuals familiar with ASCE programs and committees, as well as NOAA programs and laboratories, and is the working body responsible for executing the actions identified based on the following primary functions:

- Promoting an understanding of the needs of the civil engineering community, especially with regard to weather and climate information in support of the establishment and application of codes and standards;
- Promote clearer articulation of specific capabilities within NOAA that may be relevant to the establishment of ASCE codes and standards;
- Promote an all-NOAA approach by communicating these needs and capabilities across the broad landscape of NOAA programs; and
- Increase coherence across key ASCE bodies involved in the establishment and application of ASCE codes and standards by promoting unified approaches to understanding future changes in weather and climate extremes as appropriate.

The Task Force should meet virtually every other month starting in November 2021 for a duration of two years that may be renewed at the discretion of ASCE and NOAA and will be chaired by the principal investigator with co-chairs from NOAA and UMD-CTSM. Members should possess expertise in engineering design, construction, standard setting, climate modeling, statistics, and weather and climate observation. Roughly half of the Task Force should be made up of members with a working knowledge of NOAA programs, especially with regard to internal and externally funded earth system science, climate modeling, earth system observing, data and model output management and accessibility, and climate tool and service development across all relevant NOAA line offices. The balance of the Task Force should have significant experience with ASCE codes and standards, especially in characterizing probability of exceedance of weather or climate sensitive design parameters, their use in codes and standards, and in the accounting for non-stationarity.

Members of the Task Force as of April 2023 are:

- Co-Chairs
  - Bilal M. Ayyub, UMD
  - Benjamin DeAngelo NOAA, OAR/Climate Program Office
  - Dan Walker, EA Engineering, Science, and Technology, Inc. (PBC) and UMD

- Department of Commerce Members
    - Debbie Lee, NOAA OAR/Great Lakes Environmental Research Laboratory
    - Dan Barrie, NOAA OAR/Climate Program Office
    - Joe Pica, NOAA/NCEI
    - Joseph Barsugli, NOAA PSL and University of Colorado, Boulder
    - Mark Osler, NOAA National Ocean Service
    - Scott Weaver, White House Office of Science and Technology Policy
    - Terri McAllister, NIST Community Resilience Group Leader
- ASCE Members
    - Brian Parsons, ASCE/EWRI, ASCE Chief Sustainability Officer
    - Don Scott, President, ASCE SEI, Don Scott Consulting
    - Jennifer Goupil, ASCE/SEI Codes, Standards, and Technical Initiatives
    - John Dai, Chair, ASCE Committee on Climate Intelligence for Codes and Standards
    - Mari Tye, ASCE/CACC, NCAR
    - Michelle Barbato, ASCE/CACC/SEI, University of California - Davis
- Other Federal Partners
    - John Ingargiola, FEMA National Initiative to Advance Building Codes

Appendix B. Workshop Scope and Objectives

The Task Force identified an opportunity to initiate the necessary technical advancements, links, and processes to allow for the regular production of key data sets used in the design of climate-resilient infrastructure and having climate-ready engineering practices. Two workshops were convened to: (1) define the needs of civil engineering practices to take account of a changing climate, and (2) identify and analyze the current and future capabilities of NOAA to provide the best available climate and weather information to meet those needs. Such results can be used to define data sets tailored to be directly ingested into the update cycle of key codes and standards of the ASCE with particular focus on ASCE/SEI 7: *Minimum Design Loads for Buildings and Other Structures*, and other ASCE design documents such as ASCE/SEI 24: *Flood Resistant Design and Construction*.

The data sets can: (1) build on available NOAA products at the Technical Readiness Level (RL) 2 (i.e., applied research) or higher; and (2) as necessary, move them to RL 7 (i.e., prototype system demonstration) over the course of the coming years by having them readily available for use in engineering practices; and (3) identify any gaps and needs for further research. To this end, the workshops engaged key NOAA offices and laboratories.

The Task Force envisioned the workshops as part of a practice-to-practice development process that typically consists of the following steps: (1) obtaining inspiration by needs in practice, e.g., sections in standards; (2) developing a methodology (e.g., projections with downscaling and associated uncertainties); and (3) producing technical basis documents for revised practices to meet these needs in a format and on a timescale to facilitate adoption and utilization. In this context, practice-to-practice development builds on robust, consensus results from reputable climate science providers (e.g., NOAA and other United States modeling centers) to connect model projections to the localized needs of planners and engineers in achieving climate-ready infrastructure.

Working with the Task Force, the development team examined key weather and climate impacts of relevance to engineering practice and identified the following climate hazards for defining the objectives and scopes of the two workshops: (1) extreme temperatures leading to changes in mechanical properties of materials, loads, and/or affecting environmental conditions including soil strength; (2) intense rainfall events and associated runoff and flooding; (3) wind related hazards from straight-line winds and hurricanes; and (4) coastal hazards such as storm surges and waves as sea level rises. It is envisaged that such estimates and projections will be generated by transforming projected weather and climate variables into projected engineering hazards for both the most likely and extreme hazard attributes, with uncertainty estimates and associated conditions at scales appropriate for engineering practice for selected regions, scales, time periods, and future climate scenarios.

Structured Breakout Discussions

The Task Force provided the following list of questions to be addressed during the breakout sessions.

Defining Civil Engineering Needs

- What are the ASCE standards or manuals of practice (please be specific) and key geophysical parameters including observed values, model output, or other numerical input to the engineering practice (engineering planning, design and operations) discussed in your breakout?
- Please identify those geophysical parameters important to engineering design and operations as discussed in your breakout (please be as specific as possible).
- What temporal or spatial scales were associated with each geophysical parameter? If those scales of interest vary by use (differ between or within relevant standards or manuals of practice), please organize your response according to the reference ASCE guidance document.
- How sensitive is the application of each parameter to uncertainty? Again, if that sensitivity varies by use (differs between or within relevant standards or manuals of practice), please organize your response according to the reference ASCE guidance document.
- Please discuss (by parameter) any constraint or use case that should be considered in determining when a vetted product would be needed.
- What significant use cases were identified that could not be attributed to a specific ASCE guidance document at this time?
- What capabilities (approaches and products) are currently employed in civil engineering practice to characterize key geophysical parameters discussed above based on historical observations (assume stationarity). If those solutions vary by use (differ between or within relevant standards or manuals of practice), please organize your response according to the referenced ASCE guidance document.

Identifying Proposed NOAA Climate Products/Information and Approaches for Addressing Civil Engineering Needs

- What capabilities currently exist or could be rapidly developed to characterize key geophysical parameters discussed above at future time horizons with non-stationarity of value to civil engineering practice. If those solutions vary by use (differ between or within relevant standards or manuals of practice), please organize your response according to the referenced ASCE guidance document.
- For those use cases for which an existing capability does not currently exist to characterize key geophysical parameters discussed above at future time horizons with non-stationarity of value to civil engineering practice, summarize any approaches explored with any key limiting factors identified. Again, to the degree possible, please organize your response according to the referenced ASCE guidance document.

Two workshops were convened for leveraging earth system science and modeling to inform civil engineering design as follows:

- Workshop I – Temperature and Rainfall (September 9 and 23, 2022)
- Workshop II –Extreme Winds and Coastal Hazards (October 21 and 28, 2022)

The outcomes of these workshops are provided in four chapters corresponding to the three climate hazards and one region with their respective workshop breakouts.

B.1. Workshop Purposes and Desired Outcomes

B.1.1. Workshop I: Temperature and Rainfall

September 9 and 23, 2022
ASCE Headquarters – Bechtel Conference Center
1801 Alexander Bell Drive, Reston, VA

Purpose and Desired Outcomes:
It is broadly recognized that non-stationarity in the weather and climate system, especially on timescales greater than 20 to 30 years presents significant challenges for civil engineering design and system operations. This challenge underlies the motivation behind the emerging partnership between NOAA and ASCE. This workshop is intended to be the first of a series, exploring in detail how NOAA data collection, modeling efforts, and research could be leveraged to develop actionable information needed by civil engineering practitioners to address various climate related hazards during the design phase of projects. Specifically, the workshop should identify specific actions that could be taken by NOAA to provide actionable information needed to characterize loads due to temperature and precipitation extremes and in a manner consistent with standard engineering practice as manifest in ASCE codes and standards or relevant MOPs.

B.1.2. Workshop II: Wind and Coastal Hazards

October 21 and 28, 2022
ASCE Headquarters – Bechtel Conference Center
1801 Alexander Bell Drive, Reston, VA

Purpose and Desired Outcomes:
It is broadly recognized that non-stationarity in the weather and climate system, especially on timescales greater than 20 to 30 years presents significant challenges for civil engineering design and system operations. This challenge underlies the motivation behind the emerging partnership between NOAA and ASCE. This workshop is intended to be the first of series, exploring in detail how NOAA data collection, modeling efforts, and research could be leveraged to develop actionable information needed by civil engineering practitioners to address various climate related hazards during the design phase of various projects. Specifically, the workshop should identify actions that could be taken by NOAA to provide actionable information needed to characterize future extreme winds and loads due to straight-line winds and components of coastal hazards (including sea-level rise) in a manner consistent with standard engineering practice as manifest in ASCE codes and standards or relevant MOPs.

Appendix C. Acronyms and Abbreviations

AEP	Annual Exceedance Probability
AF&PA	American Forest & Paper Association
AFI	Air Freezing Index
AFI-100	100-year return interval air freezing index
ANSI	American National Standards Institute
ARA	Applied Research Associates
ASCE	American Society of Civil Engineers
MOP 77	Design and Construction of Urban Stormwater Management Systems
ASCE/SEI 24	Flood Resistant Design and Construction
ASCE/SEI 7	Minimum Design Loads for Buildings and Other Structures
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATI	Air Thawing Index
BFE	base flood elevation
CACC	Committee on Adaptation to a Changing Climate of ASCE
CAP	Climate Adaptation Partnerships (formerly Regional Integrated Sciences and Assessments or RISA)
CICS	Subcommittee on Climate Intelligence in Codes and Standards of CACC
CMIP	Coupled Model Intercomparison Project
CMIP5	Coupled Model Intercomparison Project Phase 5
CMIP6	Coupled Model Intercomparison Project Phase 6
CMRI	Flood scale factor for mean recurrence interval (MRI)
CONUS	Continental United States
COPRI	Coasts, Oceans, Ports, and Rivers Institute
CPO	Climate Program Office
CTSM	Center for Technology and Systems Management
ds	Depth of flood
df	Design stillwater flood depth
EWRI	Environment and Water Resources Institute of ASCE
FEMA	Federal Emergency Management Agency
GCM	General Circulation Models
GFDL	Geophysical Fluid Dynamics Laboratory (NOAA)
GHG	Greenhouse Gas
HPD	Hourly Precipitation Data
HRRR	High-Resolution Rapid Refresh
HVAC	Heating, Ventilation, and Air Conditioning
ICAMS	Interagency Council for Advancing Meteorological Services
ICC	International Code Council
IDF	Intensity-Duration-Frequency
km	Kilometer
LRFD	Load and Resistance Factor Design

MIT	Massachusetts Institute of Technology
MOP	Manual of Practice
MOU	Memorandum of Understanding
MRI	mean return interval
NClimGrid	NOAA Monthly United States Climate Gridded Dataset
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering and Medicine
NCAR	National Center for Atmospheric Research
NCEI	National Centers for Environmental Information of NOAA
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
PMP	Probable Maximum Precipitation
PSL	Physical Sciences Laboratory (NOAA)
RC	Risk Category
RCP	Representative Concentration Pathway
RL	Readiness Level
SEI	Structural Engineering Institute
SLR	Sea Level Rise
SNAP	Scenarios Network for Alaska + Arctic Planning
SPEAR	Seamless System for Prediction and Earth System Research (NOAA)
T&DI	Transportation & Development Institute
Task Force	ASCE-NOAA Task Force for Climate Resilience in Engineering Practice
UMD	University of Maryland, College Park
USACE	United States Army Corps of Engineers
USGCRP	United States Global Change Research Program
USGS	United States Geological Survey

Appendix D. Climate Sensitive ASCE Standards and Manuals of Practice

A review of the 43 active ASCE standards that are sensitive to changes in weather and climate extremes helps illustrate how complex interactions between engineering practice and environmental conditions can be (see Table 1.1). The remaining ASCE standards were simply insensitive to environmental conditions or covered engineering activities of such a short duration that changes in weather and climate extremes were not relevant.

For example, ASCE/SEI 49: *Wind Tunnel Testing for Buildings and Other Structures*, last updated in 2022, provides the minimum requirements for conducting and interpreting wind tunnel tests to determine wind loads on buildings and other structures. Because these are purely controlled tests, they are not affected by changes in environmental conditions outside the facility; however, the guidance on interpreting results may require clarification as research evolves. Another example is ASCE/SEI 37: *Design Loads on Structures During Construction*, which describes the minimum design requirements for construction loads, load combinations, and load factors affecting buildings and other structures that are under construction. Last updated in 2015, it addresses partially completed structures as well as temporary support and access structures used during construction. Although these structures must be designed and constructed to withstand various weather extremes, their service life is sufficiently short that long-term changes in weather and climatic extremes are likely not relevant but may warrant further examination in future.

Appendix E. ASCE-NOAA Memorandum of Agreement and Leadership Summit

E.1. ASCE-NOAA Memorandum of Agreement (MOU)

Leaders from NOAA, ASCE, and the UMD CTSM held a summit on February 1 and 2, 2023, to discuss how the Nation's engineering profession can account for climate change in the design and construction of future building and infrastructure projects. A MOU was unveiled during the summit, detailing the ways that NOAA's science and products will be used to inform the building and civil engineering codes, standards, and best practice manuals developed by ASCE. Information from the summit will inform future exchanges and conversations. The MOU is available on the following websites.

- https://www.asce.org/-/media/asce-images-and-files/communities/institutes-and-technical-groups/environmental-and-water-resources/documents/asce-noaa-mou.pdf
- https://www.noaa.gov/sites/default/files/2023-02/MOU_between_the_American_Society_of_Civil_Engineers_and_NOAA.pdf

E.2. ASCE-NOAA Leadership Summit (2023)

ASCE and NOAA convened a leadership summit on climate resilience in engineering practice on February 1 and 2, 2023. The summary of the summit is available at https://nvlpubs.nist.gov/nistpubs/gcr/2023/NIST.GCR.23-042.pdf.

Participants at the ASCE-NOAA Summit February 2, 2023.

The ASCE-NOAA MOU signed on February 1, 2023

Opening session of the ASCE-NOAA Summit on February 2, 2023

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