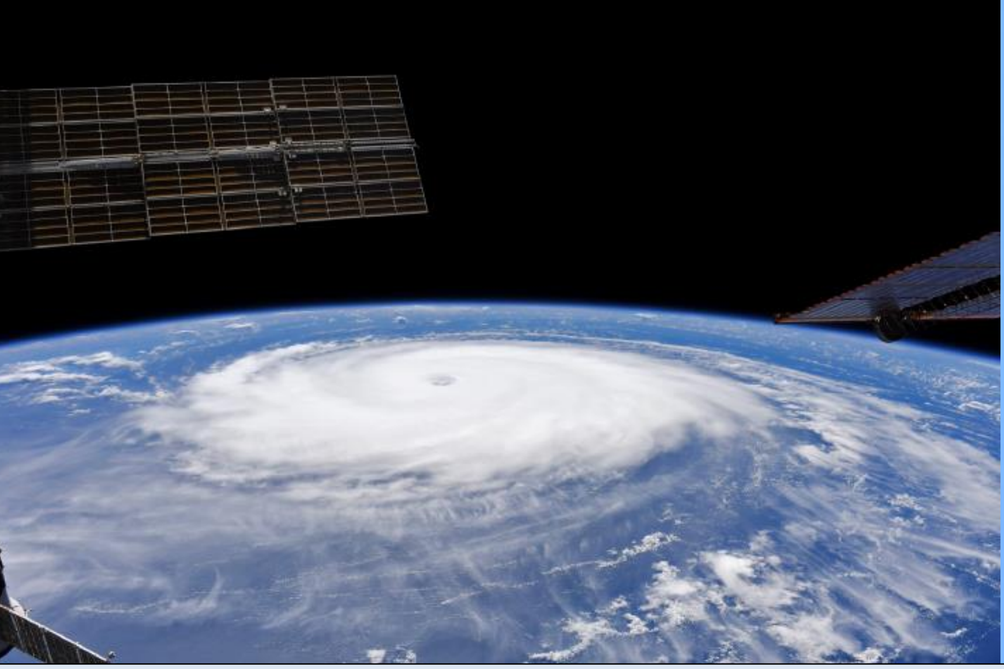

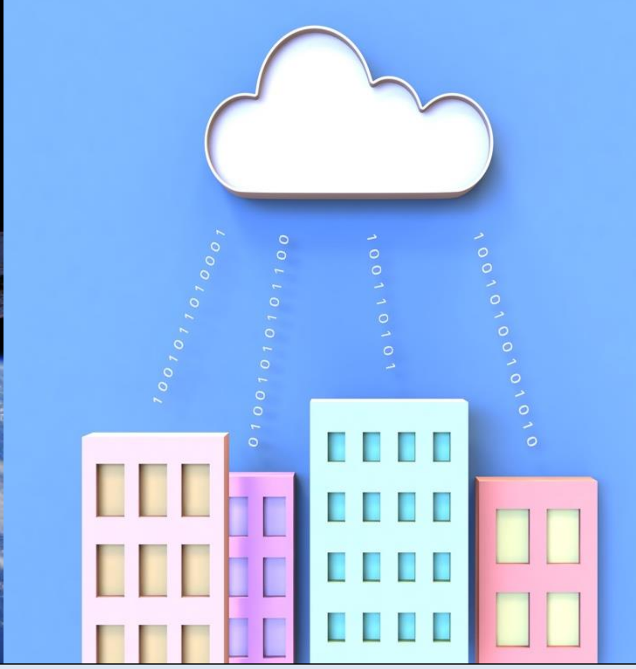

Who Will Make Sense of All the Data?
Assessing the Impacts of Technology on the Weather, Water, and Climate Workforce

American Meteorological Society
Policy Program Study
October 2021

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Who Will Make Sense of All the Data? Assessing the Impacts of Technology on the Weather, Water, and Climate Workforce

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American Meteorological Society

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Executive Summary

Rapid technological development is a powerful driver of change across the whole of society. Within the weather, water, and climate (WWC) enterprise, technological shifts have enabled advances in observations and research that expand scientific capabilities and understanding. These shifts have in turn touched nearly every aspect of the WWC workforce, from the availability of workers to the skills that they need. Moreover, changes in technology will almost certainly continue to alter challenges and opportunities within the WWC workforce in the decades to come.

This AMS Policy Program study explores the state of the technological landscape in WWC science and its implications for employers and employees across the public, private, and academic sectors. Synthesizing the perspectives of experts throughout the WWC enterprise, along with additional analysis, we detail the opportunities and challenges for workforce adaptation that are required as a result of technological advancement. Additionally, we discuss frameworks to support the current and future workforce across all career levels within the enterprise.

We find two major technological drivers of WWC science: ever-increasing data availability and advancing computing capacity. The former stems largely from the proliferation of improved sensor technologies and networks, along with small satellites; the latter from specialized computer chips and cloud resources. These developments have spurred the uptake of artificial intelligence and machine learning as well as a shift in the dominant programming language within the workforce.

In response to the increasing variety of programs and systems enabling work with data, skills such as data management and the ability to problem solve and think at a systems level are likely to be broadly applicable to WWC science. The continual development of new technologies will likely also favor personal adaptability and flexibility that allows lifelong learning with the ability to quickly adopt new tools. Competition within and beyond the enterprise for employees with these skill sets presents a clear challenge for employers and raises many questions regarding the future of the WWC workforce.

Potential frameworks to address these technological challenges and questions include a conscious push to improve communication and collaboration across sectors as well as a renewed approach to education for early as well as mid- and late-career individuals.

We identify six overarching concepts that underpin further efforts to advance the WWC workforce:

- Needs emerging from the rapid advance of data and computing capacity are strong technological drivers on the WWC workforce.

- Technological change will be rapid but not uniform in its impact on the workforce: differences may be reflected in field of expertise or career stage.

- The enterprise must holistically consider the appropriate use and support of technologies such as cloud computing and artificial intelligence, while maintaining flexibility as new tools emerge.

- Technical mindsets integrating data management and systems-level thinking are likely to be broadly applicable in the long term.

- The rapid introduction of new tools demands a renewed approach to education and training that encompasses multiple disciplines and stages of career development; cross-sector partnerships are vital to these efforts.

- Multiple approaches are possible to address challenges; solutions may be blended to enable the most optimal outcomes for individuals, organizations, and the enterprise as a whole.

AMS is engaged in multiple ongoing efforts to better understand workforce challenges and opportunities in order to help meet the future needs of the enterprise and support the careers of all enterprise members.

1. Introduction

The workforce acts as both an influence on and a reflection of society. With the world currently in the midst of a period of rapid change, the workforce is accordingly transforming as well, responding to numerous and interconnected technological, social, and environmental shifts. These shifts touch every aspect of the workforce and in turn affect individual, community, and societal success.

The rapid and ongoing changes in the world and workforce have far-reaching implications for the weather, water, and climate (WWC) enterprise, which consists of employers, employees, and supporting infrastructure across multiple sectors. While factors such as globalization, automation, and generational transitions broadly influence what types of work are being done, —as well as where, when, how, and by whom—the WWC enterprise has unique characteristics that also shape its work and workforce. WWC science is highly visible, connecting directly to the lives and prospects of everyone on the planet. The enterprise is also highly collaborative across governments, industry, nonprofit organizations, and academia. Though they may share some similarities, each of these sectors possesses different capabilities and weaknesses and therefore reacts differently to change.

As a scientific and professional society, helping the WWC enterprise understand and navigate its various challenges and opportunities is central to the mission of the American Meteorological Society. The AMS Policy Program has previously contributed to the body of work on the future of the WWC workforce, identifying opportunities and needs for advancement based on technological and societal drivers.[1] However, there remains a critical opportunity to further improve understanding of enterprise needs, including those of employers, employees, and the infrastructure that enables work to be done. Addressing these needs will enable the enterprise to more effectively build and support a skilled and resilient workforce capable of surmounting the challenges of the coming decades and beyond.

While societal and environmental changes are important workforce drivers, this AMS Policy Program study focuses primarily on the impacts of rapid technological changes on the WWC enterprise. Innovation in the technologies and tools available to the enterprise enables advances in observations and research that expand scientific capabilities and understanding, ultimately benefiting society. The continued success of the enterprise therefore depends on its ability to attract, train, and retain a workforce equipped with the skills and knowledge to make use of new and emerging technologies to their full potential.

This Policy Program study is based primarily on three workshops that AMS hosted virtually in February 2021. In order to form a comprehensive picture of the impacts of a changing technological landscape across the diverse and broad enterprise, each 2-hour workshop centered on a different aspect of the enterprise: a) basic and applied research, b) hardware and instrumentation, and c) interpreting and communicating science. The workshops drew a total of 29 participants from across the public, private, and academic sectors, with additional input provided through one-on-one conversations following the workshops. This study synthesizes insights and ideas shared in these workshops and previous bodies of work and provides further analysis.

Here, we first explore the state of the evolving technological landscape and identify key drivers of technological change within the WWC enterprise. We then identify and explore the challenges these drivers place on the WWC workforce and enterprise broadly alongside frameworks to support the current and future workplace across three key topic areas: new tools, skill acquisition, and attraction and retention of employees. This is followed by a discussion regarding the implications of these demands and solutions for the WWC employees, the employers, and the enterprise as a whole.

2. Characteristics of the evolving technological landscape

a. Increases in data availability and computing capacity

The current technological landscape across the WWC enterprise is defined largely by the ongoing coevolution of available data and computing capacity. Through oceanic, ground, aerial, and satellite-based resources, the enterprise observes physical systems, biological resources, and social institutions like never before. Simultaneously, the ongoing development of higher-performing and more specialized hardware and software continues to enhance computing power within and beyond the enterprise. The developments in data and computing capacity have occurred alongside broad societal and scientific advances that have changed how we think about and process information. They are also not wholly independent progressions: advances in one area often play a role in advancing the other.

Sources of WWC data are increasingly abundant and diverse. The proliferation of new and improved sensor technologies and networks, including remote sensing and the Internet of Things (IoT), has increased the amount of data that can be collected and exchanged across devices and systems. Other forms of nontraditional data collection are also on the rise, aided by technology and social media. For example, citizen science efforts, such as NASA's GLOBE Observer, enable members of the public to contribute to the data production process of numerous Earth observation projects (e.g., cloud formation, land cover, mosquito habitats) through the use of smartphones, computers, or other forms of mobile technology. Moreover, the decreasing cost of launching material into space has allowed small satellites, such as CubeSats, to become a more viable option for the collection of certain types of Earth observation. While some observations are still only possible with large or expensive satellites, the increasing diversity of space technologies creates new opportunities for various sectors to be stakeholders in these endeavors. However, as the number of available observations grows so too does the challenge of obtaining relevant and meaningful information from these data.

The monetary and societal value of data is maximized when these data are usable to a range of stakeholders. In the face of an influx of data into the WWC enterprise, enabling data and applications to interface efficiently across sectors and disciplines is therefore likely to be a challenge for the workforce and the enterprise broadly. This may entail using a common format for data and metadata and taking other steps to increase data accessibility while navigating proprietary concerns. Quality control may also be an issue as the amount of available data increases, particularly from IoT and other nontraditional data sources. Developing widespread standards and best practices for data use within the enterprise is likely to become a priority.

The ability to use this abundance of data would not be possible without widespread advances in computing capacity, including storage and processing technologies. Computer chips have become smaller, faster, more efficient, and highly specialized, allowing for more efficient operations. Graphics processing units (GPUs), once primarily used for image rendering for video games, are increasingly common across all forms of computation as a means through which to handle multiple operations simultaneously. Moreover, improvements to memory, record-writing, and resilience capabilities within disk drive, array, and server technologies have allowed greater amounts of data to be stored and retrieved at faster speeds and with the use of less power. The increasing virtualization of servers and storage has also enabled the continued creation of vast amounts of data, as data can be accumulated with less constraint from the physical limits of individual systems. Notably, the ready scalability of this infrastructure has decoupled access to high performance computing resources from university of government funding.

b. External influences

This evolving technological environment is also characterized by newfound pressures to produce detailed science and a need to adapt quickly. External influences, including industry users, the public, and others who rely on WWC data, may drive expectations for more accurate, downscaled, and higher-resolution information to be disseminated by the WWC enterprise. This demand encourages a cycle that continually seeks the production of more granular information with the use of both specialized instruments and the increased capacity for data storage and computation. Additionally, most, if not all, of the new technology and data made easily accessible and available to the WWC enterprise has been developed over a relatively short time span, demonstrating the rapid pace of change across the various sectors of the WWC enterprise.

As advancements in both hardware and software increase capacity to manage and analyze data, the WWC enterprise has more and better opportunities to utilize the data it collects. The enterprise now can employ capabilities such as high-resolution forecasts and probabilistic forecasts to produce more detailed projections, facilitate the distribution of services, and further enable decision-making. These new capabilities represent exciting opportunities to apply and communicate science for the broader benefit of society, such as responding to the pressures of climate change or the renewal of infrastructure on a large scale, both of which require detailed information on current and future conditions. The production of model outcomes with increasing amounts of data necessitates data management, interpretation, and communication—emphasizing the sometimes cyclical nature of data abundance and technological capacity advancement.

3. Changing tools in the WWC workforce

In response to the increase of available data, the enterprise is turning to a variety of technological tools and processes to advance its observations, science, and services. While many of these tools have existed for decades (e.g., the field of artificial intelligence was first acknowledged as a research discipline in 1956), the requisite technological capacity for them to be used effectively within the enterprise has often not existed until recently.[2] These tools encompass every aspect of the enterprise, from computing to data analysis and predictions, and have enabled different branches of the enterprise—most notably the private sector—to take on tasks that may have previously been out of reach. However, this is not the only enterprise to be affected by such technological drivers. As the skills needed to use these tools become more broadly valued, competition within and beyond the WWC enterprise for knowledgeable and skilled workers increases.

a. Computing architecture

Improvements to data processing capabilities have impacted the favored computing architecture within the WWC enterprise. The enterprise has historically relied on high performance computing (HPC) systems to produce weather and climate information at a large scale. The capacity of HPC has been newly accelerated by the use of GPUs, which are optimal for work with artificial intelligence (AI) and machine learning (ML) (see section 3e). As a result, WWC scientists are able to run increasingly powerful weather and climate simulations, including small-scale predictions. However, GPUs are a supplement rather than a replacement for traditional central processing unit (CPU) systems, which remain necessary to quickly perform diverse tasks in sequence. It is therefore critical that WWC agencies with access to high-level processing understand future needs for GPU and CPU systems to ensure that their workforce is equipped to produce effective science. These systems require significant investment to construct and maintain; the majority of the future WWC workforce may never interact with one. Instead, computing architecture within the enterprise—and the resulting workforce needs—is becoming increasingly tied to the cloud.

b. Cloud computing and open-source infrastructure

The growing need to increase data storage and reduce time spent transporting data has led the enterprise to rely on cloud computing for the purposes of accessing and manipulating data. Cloud computing promises flexible and cost-efficient access to computational resources for individuals and organizations within the enterprise, freeing up time and resources with which to carry out their mission and goals. This is particularly useful for stakeholders within the enterprise, including international users, without the resources to obtain and maintain HPC systems to support their programs, models, and products.

The current cloud ecosystem consists of various commercial cloud services, often provided by powerhouse technology companies such as Amazon, Microsoft, and Google, alongside open-source platforms and tools. Cloud operations may be private (wholly dedicated to one organization), public (shared by multiple organizations), or a public–private hybrid. Many private sector organizations have wholeheartedly embraced cloud technology, some electing to operate exclusively within the cloud. Conversely, the public sector has been slower to transition fully to the cloud, in part due to existing investment in multimillion dollar HPC infrastructure.[3] The public sector must grapple with the challenge of whether to commission next-generation HPC systems, follow suit in moving operations to the cloud, or engage in efforts to facilitate a hybrid approach. Part of this challenge lies in data volume—NASA alone estimates that it could potentially be storing upward of 250 Petabytes of data on the commercial cloud by 2025.[4] As such, it is possible that the amount of data generated by the enterprise may outpace the ability of the cloud to store data for end users. Furthermore, there are likely to be concerns of cloud platform reliability and security at the large scales needed for public sector use. Instances of cloud system failure could become highly detrimental, particularly as cloud services consolidate due to commercial acquisition. The need for redundancy makes it unlikely that cloud alternatives will fully replace the use of HPC within the enterprise.

However, a wide range of government agencies produce public data that the WWC workforce relies upon. By adopting cloud infrastructure and hosting the data there, the data may become more accessible and available to the public to inform and advance WWC sciences and services. To utilize publicly available data more efficiently, the public sector could collaborate to support a public cloud platform that includes both the data and tools on the platform to help end users manage and create value from the data. This centralization of data and tools on a user-friendly, open-source cloud platform may provide the enterprise an opportunity to conduct science and services in an efficient manner, though other options through the private sector will continue to be available.

Currently, NOAA has moved data and information to be supported on a cloud platform: it would be a significant endeavor for the organization to additionally develop and support an on-site tool to augment the usability of the provided data. The European Weather Cloud, a joint intergovernmental endeavor between the European Centre for Medium-Range Weather Forecasts (ECMWF), the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), and cooperating member states, is a clear example of such publicly provided cloud where entities can host their applications close to the data. The current iteration provides infrastructure as a service (IaaS), with a short-term goal of providing platform as a service (PaaS) and long-term goal of offering a software as a service (SaaS) model.[5] This European cloud model, if successful, may provide inspiration or a framework for the greater weather, water, climate public enterprise. However, there is likely to be no single way of migrating to the cloud that will work for every aspect of the enterprise.

The uptake of cloud computing throughout the WWC workforce is likely to depend upon individual familiarity with various cloud setups. While the cloud has generally democratized means of sharing, managing, and analyzing data, a degree of siloing exists as a result of the different solutions offered by different cloud providers such as Amazon, Microsoft, or Google. For users with limited technical experience who work with these proprietary toolkits, this setup may limit the overall flexibility of cloud computing by discouraging movement between providers. However, for users with an understanding of cloud-optimized formats, workflows, and packages, transitioning between commercial and open-source platforms as needed is less of an obstacle. New tools are constantly being developed, often in collaboration, to promote cloud expertise. The Pangeo Cloud project (https://pangeo.io/cloud.html), an open-source community for the geosciences, is one example of a collaborative effort to provide state-of-the-art open-source tools for cloud-based data analysis.

As the WWC enterprise increasingly accepts cloud computing as a pillar of data management it must include and empower individuals familiar with cloud-native network tools, software, application, and practices. The responsibility of WWC employers to hire, train, and retain these skilled individuals is a crucial means of remaining a high-functioning workforce in a rapidly advancing technological environment. However, necessary levels of proficiency in cloud computation will vary across the disciplines and roles of the WWC workforce. Understanding what degree of proficiency is required by whom and how to manage resources to train the workforce is a present challenge. Additionally, users that best understand how to adapt their code to the cloud and how to bring their modeling and program tools to the cloud may have better success optimizing the potential of cloud computing for the geosciences.

c. Programming languages

The programming language Fortran has historically been the building block of computing within the enterprise. For decades, WWC scientists have used Fortran to develop meteorological, ocean, and climate models, often in conjunction with HPC. As a result, a significant amount of legacy code, particularly within the public sector, exists in Fortran. However, while Fortran is primarily used for numerical and scientific computing, researchers are increasingly turning to the general-purpose programming language Python to handle data of all types and interface with a variety of software applications. Expanded GPU capabilities enable Python to be readily used for HPC; additionally, it is one of the most popular languages for work with AI and ML.[6] As Python becomes increasingly popular within and beyond the enterprise, the enterprise will likely need to reevaluate its reliance on Fortran. Improved systemic support of Python might not only help the existing WWC workforce perform more efficiently but also increase the pool of available workers that the enterprise can draw on. Conversely, if the enterprise fails to keep up with shifts in preferred programming languages, employers may have an increasingly difficult time finding new employees that can adeptly work with existing Fortran-based programs. This balance between new and outdated languages will likely repeat in the future as programming languages further evolve, indicating a need for the workforce to be flexible to changes.

d. Artificial intelligence and machine learning

While traditional computing systems can analyze vast amounts of weather and climate data, AI systems—including machine learning, neural networks, and deep learning—can be trained to look at these massive amounts of data and recognize patterns, providing additional insights. This potentially allows WWC scientists to produce more precise and accurate simulations and to facilitate decision-making. The use of more powerful HPC, often featuring GPUs, has enabled the geosciences to harness the power of AI and ML to a greater and more specialized degree than has previously been used within the enterprise. However, more work is needed before AI can be considered a commonplace tool across all sectors.

Though the use of AI and ML in the WWC enterprise is an opportunity to expand understanding and produce more advanced outcomes, these tools require an additional knowledge base on top of existing specialties that professionals in the workforce are expected to have. While it is possible for scientists to make use of the output of models without complete understanding of the models' processes, the ability to diagnose problems and test new theories is dependent on such understanding. Additionally, because many modern tools for working with ML are built using Python, Python can be seen as a required secondary skill for applying AI to WWC science. The traditional academic structure founded on post-secondary degrees is likely not currently well positioned to provide the breadth and depth of knowledge needed to produce professionals adequately equipped with both geoscientific and AI/ML knowledge. As the application of AI to WWC problems becomes increasingly popular, individuals throughout the workforce are calling for more training and information on AI/ML. The number of conferences on AI are doubling annually, workshops for AI are on the rise, and AMS is launching a new journal "Artificial Intelligence for the Earth Systems" in fall of 2021.[7] Additionally, the NSF now funds the AI Institute for Research on Trustworthy AI in Water, Climate, and Coastal Oceanography, exemplifying the emphasis on these tools and how the WWC enterprise is putting funding, time, and resources into understanding their capabilities and how to best use them.

Bias exists within the creation, training, and optimization of data, algorithms, and models, therefore affecting the outputs of AI and ML used by the WWC enterprise. If an AI system is trained to predict hail based on reports of hail from urban areas, its forecasts might subsequently be less accurate in less densely populated areas. If a programming team consisting solely of English speakers is evaluating responses to hurricane evacuation orders, they may overlook data from Spanish-speaking neighborhoods. Conscientious attention to ethical considerations must be incorporated into how the enterprise makes use of AI as its prevalence continues to spread. The aforementioned AI Institute for Research on Trustworthy AI attempts to address this very concern at the outset by partnering with community-based decision-makers and end users of their AI techniques. Current attempts to understand what biases are included in models is important to understand how to use and communicate the output of models or how to minimize the bias in the future. The inclusion of diversity in ideas and perspectives, or more interdisciplinary methods of research, may reduce the prevalence of bias to benefit the system outcome. Discussions surrounding the role of human insight, specifically geoscience knowledge and experience, in applying AI output will likely continue to influence how the community uses AI in the future. In particular, whether data and technical scientists learn about geoscience principles to interpret AI outputs or geoscience professionals understand how to work with AI will impact how data and information is communicated.

e. Future use of emerging technologies

The five highlighted technological tools and issues are, individually and in conjunction, dramatically shaping the technological capabilities of the WWC enterprise, the demands on the existing WWC workforce in order to remain successful, and the pool of potential WWC workers as they are relevant to and attracted to the mission of the WWC enterprise. However, while these changes are occurring rapidly, and generally simultaneously, they are not likely to impact all sections of the workforce equally. Certain sectors are more able to support the uptake and use of new technology; moreover, not all technology is relevant to all sectors. Tension may also arise from the adoption of a small number of tools that are easier to teach and learn and the increased flexibility of many tools for many purposes.

These factors may influence how the enterprise as a whole chooses to respond to these changes.

Technology will inevitably continue to evolve, and with it the ability of the WWC workforce to effectively provide science and services. AI and cloud computing are the two areas that perhaps demand the greatest degree of consideration from the enterprise as to their future incorporation within the workforce. However, to treat these tools as the ultimate solution to WWC challenges and to fail to think beyond them to the next great tool would be detrimental to the future workforce. For example, while the cloud reduces limitations of HPCs such as storage space and speed, it does not entirely eliminate the issues as the models and programs still run on off-site servers and may be more expensive for certain kinds of modeling.

The WWC enterprise should not only react to the current environment but also consider the future role of technology in order to remain resilient. Enterprise or organizational resilience can be facilitated by an emphasis on adaptable and flexible mindsets, skill sets, and ways of learning to better enable reactions to changing future technology.

4. Skill acquisition

In an enterprise where new technologies and tools advance at a rapid pace, developing the skills to adapt to these changes and effectively utilize these new opportunities is of paramount importance to the workforce. However, existing frameworks of skill acquisition in the workforce are often not sufficient to enable the seamless integration of relevant technical skills. The traditional mechanisms for skill acquisition (i.e., college degrees) remain an established fixture in the workforce training process yet may need to be supported by other learning programs.

a. Academia and educational instruction

The rapid pace of change within the technological landscape has exacerbated gaps in how academic institutions prepare students for workforce success. This is not a problem directly caused by the onset of cloud computing, an abundance of data, or other technological changes; rather, it is a symptom of a fairly rigid academic structure, sparse communication between educational institutions and the enterprise more broadly, and a lack of common hardware infrastructure and software tools between and among disciplines. Recipients of post-secondary degrees achieve these designations by completing a predefined set of courses, projects, or internships. These courses are often specific to their fields and allow students to become better trained in relevant information for their future career. Academic institutions generally have involved processes for amending curriculum core courses or requirements, allowing for degree programs to remain relatively stable over time and for students and professors to set their expectations accordingly. However, this also results in the newest technologies and skills being consistently a few years out of date by the time they are implemented into classrooms. This puts students at a disadvantage as they graduate. Specifically, as cloud computing and other data analysis skills are emphasized in the WWC workforce, college degrees in atmospheric sciences or meteorology are slow to incorporate comprehensive computational courses in the curricula or have a dearth of professors with the relevant knowledge to teach such courses. Additionally, with already rigorous and full curricula, there is little academic consensus on what topics and subjects to remove from syllabi in order to make room for new computer courses, as adding more requirements is likely unsustainable. The onus is placed on students, rather than the institutions, to determine what computer science knowledge is necessary for employability in this evolving field. Individuals new to the field or discipline may encounter conflicting or missing information regarding what particular skills will be in demand when they graduate and begin a job search. This gap is exacerbated when a set of skills such as programming language or data analysis is not uniform across broad career fields. Consequently, recent graduates may enter the workforce lacking the knowledge and skills needed to work on real-world problems.

Though university curricula are generally not flexible enough to undergo constant and rapid change to keep up with specific iterations of technological innovation, there may be opportunities to 1) include broad computer science knowledge into existing geoscience courses, 2) require more computer science courses in the curriculum, or 3) suggest data or computing courses to atmospheric science students (though this may be difficult with the already large amount of required courses). This could expose students to the fundamental technical and computation skills heavily utilized in the present workforce and in turn make geoscience graduates more employable. Such computational science instruction could additionally be strengthened by inclusion of cloud computing specifically in the curricula. Partnerships between academic institutions and cloud providers could support widespread proficiency of an increasingly vital skill. Courses may also incorporate teaching methodologies that prepare students for lifelong learning and enable them to cope with change throughout their careers.

Forging or deepening of lines of communication directly between academia and employers within the WWC industry may provide an opportunity to clarify expectations of relevant skills, particularly as technology advances. Private employees may help enhance student exposure to “real-world problems” through collaboration in creating course modules or case studies. Students, or potentially employees, would benefit from a clear understanding of what skills are necessary for them to cultivate while undertaking a degree in order to use their time and resources wisely and be well prepared for entry-level career opportunities. Additionally, the industry would be able to influence their pool of potential hires in time with rapid changes instead of reacting to curriculum updates.

The private sector may also play an increasing role in shaping the education of the future workforce. During the COVID-19 pandemic in 2020, Google executives saw an uptick of activity on their search engine where users sought information on “good jobs without degrees”: a symptom of sudden mass unemployment. This need for a nontraditional path to well-paying jobs paired with an observed mismatch of skills sought by employers and skills cultivated in a four-year degree created an opportunity for Google to capitalize on this gap in the workforce pipeline. There are now several six-month online courses organized by Google that aim to prepare their students with in-demand project management, data analysis, and user experience design skills intended to replace a four-year degree.[8] Like Google, the WWC enterprise has the opportunity to reimagine workforce training by embracing the online learning tools and digital skills that have emerged in response to the COVID-19 pandemic.

AMS provides a variety of resources to support professional development, including its Early Career Leadership Academy as well as webinars and podcasts on different aspects of careers in meteorology and related fields. Continuing to expand and improve these offerings may help further regular communication of technological trends between sectors of the enterprise and create engagement opportunities for community members. AMS could also further assist in the ongoing education of its WWC enterprise members by supporting geoscience-oriented educational programs on relevant technology. While public, private, nongovernmental organization (NGO), and academic partnerships are already strong within the WWC enterprise, AMS can leverage its unique position as a scientific society with contacts across the enterprise to further establish and support these communication networks and create new engagement opportunities.

b. Lifelong learning

Technological disruptions also affect individuals in their mid- and late careers who may be grappling with how to best adapt to the changing circumstances within the WWC enterprise. Specific educational opportunities to suit these individuals’ needs are difficult to find. While some large organizations may offer training programs for employees, these programs may be highly specific or insufficient. Meanwhile, advanced degrees may require too much of an investment of time and money compared to career development opportunities and the rapid pace of technological advancement. Individuals may instead turn to independent learning through platforms such as YouTube or online forums. Although the quality and efficacy of these platforms may vary, independent learning currently provides the most material for those attempting to keep skills relevant and up-to-date with technological developments.

As skills and knowledge become outdated, continued training in order to sustain relevant skills individually and throughout the workforce as a whole becomes an increasingly beneficial aspect of workforce support. This situation provides an opportunity for industries, private companies, public agencies, and academic institutions to especially support mid-career personnel and supplement individuals' self-motivated continued learning processes through a variety of educational opportunities, formal and informal. An influx of mid-career training courses, lessons, or other formats of learning are not just beneficial to the individuals that are gaining these skills and the institutions that will benefit from their up-to-date knowledge but may also serve as a business incentive for institutions that are in a position to offer such opportunities.

Short-term educational experiences are one method through which the enterprise might provide opportunities for structured learning without the commitment of advanced formal education. Such experiences have the potential to accessibly introduce specialized topics or supplement existing knowledge with practical applications. They may take a range of formats or lengths: in person or online, spanning hours, days, or even weeks of content, with differing opportunities for interaction with fellow learners or teachers. Organizations offering regular short courses or workshops specializing in Earth-systems-related topics, often targeted to professionals, include NCAR/UCAR, NASA, and AMS.

Massive open online courses (MOOCs) are already a popular means for learners around the world to explore technical topics such as programming, AI, statistics, data science, and modelling. It is feasible to imagine partnerships (between federal agencies, the private sector, academic institutions, etc.) to develop or expand MOOCs in order to promote a variety of technical skills and knowledge as they apply to the WWC enterprise. However, there may also be issues of quality, availability (funding models, self-paced vs. limited enrollment), or engagement. Translating material to an online format may also create additional work or resource needs for teachers, although this burden may be less prominent now as the COVID-19 pandemic has caused a sea change in presenting online learning content. While such courses might not be able to cover proprietary material, collaborations to develop widely available general knowledge courses on technical subjects could benefit the entire community.

As a professional society dedicated to advancing the enterprise, there are several areas in which AMS is well positioned to support effective responses to technological workforce challenges. One is through the expansion of short courses and other educational programs. The popularity of existing AMS efforts in this space demonstrates the value of such courses within the WWC community: a recent course in Python and machine learning reached capacity shortly after opening registration. In addition to continuing to offer these courses, AMS may be able to expand the range of available educational offerings through involvement with MOOCs. This might include collaboration with course providers to vet existing courses, coordinate development of new courses or updates of old courses, or make curriculum recommendations.

Pursuits of lifelong learning and careers that require such commitment may not be professional preference for all members of the WWC workforce. While lifelong learning has benefits that include the ability to be exposed to new material, methods, or ideas, the process of continued education takes time, effort, and attention that individuals may prefer to dedicate elsewhere. However, the concept of lifelong learning does not have to be constrained to formalized continued education but can rather be embraced as an openness to new skills and knowledge as one continues to grow in their profession.

c. Internships

The internship system offers one approach through which to establish lines of communication between students and the workforce. When done well, internships can provide students and recent graduates with technical learning experiences beyond the theoretical applications in many curricula. Simultaneously, employers are provided with project assistance and the chance to establish connections with students and universities for the purpose of future recruitment. However, internships are the subject of conflicting opinions across sectors, preventing a consensus on how to best structure these programs. For students, there can be a conflict between accepting an internship to gain relevant workforce experience and taking on the economic burden that comes with unpaid or underfunded internships. In academia, especially at the graduate level, term-time internships or other cooperative education programs may be discouraged by faculty that view the commitments of an internship as a hindrance to successful degree completion. In public and private sectors, the time and resources needed to successfully onboard and train interns may seem to detract from the efficiency of the organization as a whole. Despite these sentiments, employers often look for hires with internship experience, expecting these students to already understand the workings of life beyond college. However, this expected outcome is dubious when many internships are structured as siloed, short-term projects. The challenge of creating internships that suit the needs of all parties is complex: students hope to learn how the workforce functions, organizations and companies want to train the incoming workforce while simultaneously remaining productive, and academic faculty aim for completion of degrees. Enterprise-wide conversation and collaboration, especially cross-sector dialogue, is in the best interest of all parties.

To support a beneficial and successful internship process, the industry may find that rethinking and reframing the current internship structure would be advantageous for the well-being of the greater workforce. As previously explored, the framing of the internship process as a drain of company resources, time, and effort with often little tangible company gain in return creates tension between the goals of various actors: students, private and public sectors, and academia. However, reimagining an internship as the opportunity to train a potential future hire or cultivate relevant skills and knowledge in an individual for the betterment of the future workforce as a whole may help ensure that internships are mutually beneficial opportunities. Academia can also provide increased support for students participating in internships by not discouraging these opportunities to explore the workforce outside of the academic sector.

d. Mentorship

Mentorships, formal and informal, are a valuable framework through which information, knowledge, and skills are passed through academic generations and other professional relationships. Mentorships are ideally bidirectional, allowing for both mentors and mentees to gain valuable insight from each other, such as the opportunity for self-reflection, exposure to different generational knowledge, skills, and values, and a trained colleague to collaborate with. In particular, mentors may instruct and guide their mentees regarding the skills and tools needed to pursue expertise within a specific discipline, a practice that is highly beneficial when these tools are relatively stable. However, the current era of technological development in which tools and the skills needed to capitalize on them turn over in comparatively short cycles presents a challenge for the mentorship framework of knowledge sharing. Mentors often instruct on the tools and skills in which they are proficient or otherwise familiar, which may become obsolete as technology evolves over time. Mentors who are not up-to-date regarding new technologies will not teach their students the skills relevant to current technological trends. Students invest substantial time and effort becoming experts in their field of study; learning skills that are obsolete or irrelevant is likely to result in less capacity to adapt to the new ones needed for career success.

5. Attraction and retention of talent

In an increasingly digital world, technical skills are broadly applicable and in high demand outside the WWC enterprise as well as within it. As a result, the WWC enterprise must contend with a high degree of cross-sector competition for talent. Attracting and retaining skilled workers is subject to both internal and external factors: a few of the most prominent are presented below.

The WWC workforce is now looking to include talent that encompasses geoscience knowledge and technical skills in order to fulfill the goals of advancing WWC science and benefiting society. With two different desired sets of skills, the enterprise is grappling with two workforce options: to attract and hire specialists or generalists. A workforce of specialists would operate such that individuals trained in narrow fields of geoscience collaborate with experts in data and computing science such as software engineers or data analysts. This would necessitate infrastructures and systems in place to enable clear communication, baseline understandings of relevant topics, and cooperation. A workforce of generalists would seek to attract and hire trained geoscientists that also have a broad understanding of data and computing science enough that their work can be done largely without outside technical assistance. The preferred option will likely vary within the enterprise and in many scenarios a blend of both options might be optimal. However, the WWC enterprise has less difficulty attracting and retaining geoscientists than it does data and computer scientists. This is due to the fact that the WWC enterprise is one of only a few career options for narrowly focused geoscientists, while it is one of many enterprise options for the broader career focus of data and computer scientists. The in-demand skills sought by the WWC enterprise, such as AI/ML and cloud computing familiarity, cloud-native capabilities, and general data management, are also valued by the technology enterprise for example, comprising mainly private sector businesses and organizations. Large, private tech companies are often in a position to offer greater salaries to individuals in possession of these desired skills, out-competing government, public, or academic institutions. The demand for technically skilled workers is not unique to the WWC workforce and will challenge the enterprise to compensate in some capacity, placing a stressor on the enterprise in a way that the demand for geoscience knowledge and skills historically has not.

The United States has historically been a top destination for science, technology, and innovation and benefits greatly from the talents of international students, researchers, and other highly skilled workers. Immigrants represent a large share of the U.S. workforce in occupations that typically require a college degree, including 45% of software developers and 42% of physical scientists in 2018.[9] However, while the United States has the highest number of immigrants of any country in the world, it is becoming a less attractive arena for the international workforce. From a global perspective, the United States has a declining reputation in terms of technological innovation.[10] Additionally, low rates of inclusion and diversity along with restrictive visa policies have created an exclusionary environment. While the inclusion of diverse minds, ideas, perspectives, and resources within the WWC workforce enhances both WWC science and society as a whole, policy factors have the potential to limit the talent pool—and technological capabilities—of the future U.S. WWC workforce. This decline in immigration of WWC students and employees may prompt the enterprise to grow the talent pool through other methods, perhaps by investing in domestic education, especially K–12 education.

The enterprise also has the opportunity to better support individuals looking to reenter the workforce after military service, maternity leave, and other personal circumstances. These workers may not be up-to-date with the latest technology used in the field; however, they represent a source of talent for the enterprise. The enterprise may therefore seek to embrace these potential employees through WWC career counseling and other career-building services.

An enterprise or sector with high rates of attraction and retention often creates supportive environments for the workforce: while this is not strictly within the scope of the technological landscape, these factors do have an effect on the future of the enterprise. Within the WWC work environment, this may look like the presence of mentorship relationships, the opportunity to advance in one's career, or the opportunity to lead or pursue new ideas. Systemic obstacles that stifle this type of support such as rigid siloed work or lack of positive interpersonal relationships between individuals may encourage those within the WWC workforce to seek these professional needs elsewhere. Additionally, to address potential attraction and retention challenges, employers in the WWC enterprise can fortify the enterprise's reputation as a place where skilled individuals would want to invest time and energy in by ensuring health and enjoyable workplace environments. The ability to work on meaningful problems, create influence and impact, and move the field forward are powerful motivators that an employer can support in order to attract potential employees. Centering the values of diversity, equity, inclusion, belonging, and accessibility along with firm commitments to accountability can create positive workplaces and partnerships across the enterprise that individuals respect and want to contribute to. It is important that commitments to inclusion, equity, and justice exist across all scales of the enterprise, including organization and management levels.

6. Discussion

The challenges and opportunities of the evolving technological landscape have both immediate and long-term implications for the entire WWC workforce. Students, recent graduates, and current workers have a vested interest in building and maintaining a skill set that supports a long and fulfilling career, while some employers, reacting to the rapidity of change and in an effort to "keep up," may be struggling to find employees with skills that address their immediate needs. Although these perspectives are not necessarily mutually exclusive, they reveal the areas in which individual and organizational members of the enterprise may ideally seek to direct their focus.

a. Implications for WWC employees

Although the skill sets of the current and incoming workforce are unlikely to be rendered entirely obsolete in the near future, it is likely that these skill sets will need to be modified to encompass a range of technological knowledge pertinent to key advancements. While work within the enterprise is incredibly diverse, cloud-native skills (particularly for multiple cloud systems), a familiarity with open-source systems, programming in Python, and knowledge of AI/ML tools and techniques are likely to be immediately useful for many employees. As the usefulness of these tools and techniques grow over time, the capability to understand technology at a systems level may become more important for the career flexibility and general employability of an individual. This is not to say that specific programming knowledge or specialized software capabilities that can then be developed for particular projects and teams are not valuable, but rather that they may contribute to a less-adaptable skill set over time. Familiarity with data management best practices and the structures of programming languages are two skills that will likely be broadly useful for any employee within the enterprise.

As greater volumes of data are produced and collected, the need to analyze, sort, and manage them are essential to the modern WWC workforce. This includes the ability to extrapolate and communicate a clear message from a growing inundation of data. Without the ability to create useful products, applications, or messages from the influx of data, the abundance of data may act as a hindrance or distraction rather than an opportunity to capitalize on increased access to information. Data management and interpretation skills will be valuable across the workforce, from communicating the probabilistic forecast that results from many model runs to engineering software that will sort terabytes or petabytes of data. Greater understanding of the principles of software engineering and the structure of computational languages and cloud platforms will also prove valuable for many within the enterprise. Comprehension of the reasons why certain computational actions are taken, not just the memorization of the steps to do so, is important for furthering independent skill and expanding computational capabilities. Though not every member of the workforce will be compelled to become experts at such depth, basic familiarity will likely be useful for communicating across individuals, teams, projects, or sectors.

At present, the skills listed above are often not taught in the context of geoscience as it relates to the WWC enterprise. For this reason, the ability to self-teach and the willingness to be adaptable and proactive in learning new skills may be important for sustained career growth. As the specifics of software programs, models, and other technologically relevant tools evolve, the broader ability to apply critical thinking is vital when facing increasingly complex WWC problems. These critical thinking skills are highly transferable and translatable, granting individuals more resilience and enabling them to pursue more flexible career paths and projects they are enthusiastic about.

b. Implications for WWC employers

Employees that come to a position already equipped with both WWC knowledge and relevant technical skills are likely to be highly desirable to employers. However, employers also have the opportunity, and arguably the responsibility, to exert influence on how the future workforce is educated and trained. Keying in on intra-enterprise communication, employers from all sectors (private and public especially) are in a position to communicate with employees the skills and training needed for success in their specific arena of the workforce. Additionally, employers are in a position to also offer information on updated and relevant tools, technology, knowledge, and other guidance to the academic sector in order to close the skills gap between graduating students and the workforce. Direction, expectations, and collaboration stemming from consistent and clear intra-enterprise communication would help organizations navigate through the quick and complex demands engendered by recent technological advancements. As such, although employers across the enterprise may vary in clout and resources, they should strive to support continued learning programs for employees of all career stages in order to ensure a modernized and efficient workforce, especially in an era of rapid technological change.

c. Implications for the WWC enterprise

In addition to the implications that technical drivers pose for individuals or organizations, the rapid pace of change and the challenges that come with adapting to such changes have implications for the enterprise as a whole. These high-level challenges are exemplified in the competition with other enterprises and sectors for hires with relevant technical skills. There are two potential strategies to address this challenge: ensuring that the pool of potential workers from which the enterprise can draw is as large as possible or ensuring the retention and long-term success of current and future workers within the enterprise. The capacity to expand the pool of potential WWC employees is influenced by factors such as the investments that the enterprise makes regarding infrastructure and technology and the expertise of workers that are sought by the enterprise. Investments are influential when they focus on systems that may "lock in" the workforce to certain technological commitments (e.g., the use of Fortran) or systems that will allow for more adaptability as time goes on. The pursuit of either avenue will have impacts on the attractiveness of this enterprise to the available global workforce. Additionally, when worker expertise is considered, the enterprise may look to recruit either individuals who are specialists within their respective fields and ensure relevant collaboration among these employees or individuals who are generalists and can broadly, but not necessarily deeply, cover more than one area of interest. This is especially relevant to the ongoing enterprise-wide struggle of determining what degree of technical expertise is needed: does the enterprise need to support and hire specialized data scientists, software engineers, and other computer-capable individuals, or should it support geoscientists but with some additional computer courses in their training? As with many seemingly dichotomous choices, there is often opportunity for a blend of responses rather than stark and absolute responses in order to ensure the best possible outcomes.

In response to the competition with other enterprises to attract and retain talented individuals, the WWC enterprise may use this academic-to-professional pipeline to flood the applicant pool. With more individuals trained in WWC science and technology, the enterprise has a greater chance of finding individuals that meet skill, knowledge, and competency needs for the enterprise to utilize for advancement.

7. Conclusions

a. Key takeaways

As a whole, the WWC enterprise is enthusiastic about the opportunities associated with new technologies but is challenged to support its current and future workforce in adapting to a rapidly changing environment. Technological drivers are changing the ways in which the enterprise conducts its science and services while also providing opportunities for further advancement across disciplines. In turn, the WWC workforce needs to adapt to these opportunities in order to effectively sustain its contributions to society. Building resilience into the workforce requires the enterprise to rethink relevant skill sets and enhance existing frameworks for acquiring skills at all stages of career development. We have identified key technical skills as those relating to the use of cloud computing, AI, and data management. As technology continues to evolve, an individual's ability to problem solve may increasingly rely upon a mindset that encompasses systems-level understanding in order to keep pace with rapid change. However, there is no singular model among employers in terms of employing data specialists as opposed to WWC scientists or attempting to recruit and train people with cross-functional skills. Nevertheless, competition within and beyond the enterprise for employees with these skill sets presents a clear challenge for the future of the WWC workforce.

We identify six overarching concepts that underpin further efforts to advance the WWC workforce:

- Rapid advancement in computing capacity and expansion in data availability are strong drivers of workforce needs in WWC.
- Technological change will be rapid but not uniform in its impact on the workforce: differences may be reflected in field of expertise or career stage.
- The enterprise must holistically consider the appropriate use and support of technologies such as cloud computing and AI/ML, while maintaining flexibility as new tools emerge.
- Technical mindsets integrating data management and systems-level thinking are likely to be broadly applicable in the long term.
- The rapid introduction of new tools demands a renewed approach to education and training that encompasses multiple disciplines and stages of career development; cross-sector partnerships are vital to these efforts.

- Multiple approaches are available to help meet workforce needs. Comprehensive solutions almost certainly depend on a combination of approaches that address individual, organizational, and enterprise-wide challenges and opportunities.

b. Remaining challenges and areas of further research

The areas of interest highlighted below may require further study or insight into how the WWC workforce and the changing technological landscape will interact with various nontechnical forces outside the scope of this study.

1) Nontechnical workforce skills

A variety of technical tools and systems have emerged that demand greater attention and understanding in order to enable an effective, efficient, and competitive WWC enterprise. However, it is apparent that nontechnical skills will also play a large role in the future workforce. There is an increasing need to train the workforce to effectively communicate scientific information both within and outside of the enterprise, particularly with the rise of social media removing many barriers between scientists and the public. Additionally, an integration of geosciences with social sciences within the workforce may help the WWC enterprise better understand how its science is used by and affects society broadly. A WWC workforce that understands the interface with society, that has experience with public relations and a familiarity with sociology or psychology, may enable more productive science and science engagement.

2) Incorporating inclusion, equity, and justice (IEJ)

While outside the scope of this study on technical challenges to the WWC workforce, it is imperative that the enterprise consider issues of inclusion, equity, and justice as an ongoing workforce challenge. The inclusion of diverse minds, ideas, and perspectives within the WWC workforce enhances both WWC science and society as a whole and will perhaps make the WWC enterprise a more attractive field for potential workers. However, members of groups underrepresented in the geosciences face multiple systemic obstacles to inclusion at every career stage and may receive lesser benefit from the science and services of the WWC enterprise.[11,12] The nexus of IEJ and technological advancements will have ramifications across the WWC community. For example: how fairness, justice, and equality are defined and determined is crucial to the process of machine learning. Algorithms and programs that support machine learning and AI will have biases, even if unintended, which is why ethical development of such algorithms is crucial to their implementation.[13] A commitment to IEJ is not only a charge to uphold and advance human rights but to ensure that the societal benefits from WWC science are widely and fairly distributed.

3) Impact of global environmental change

There is further opportunity to explore the ways in which global environmental change might interact with the WWC workforce and the changing technological landscape as a whole. As the global environment rapidly changes, the science, observation, and services provided by the WWC enterprise may become more crucial to societal response. This may increase interest in WWC careers and create a larger WWC workforce or have other implications for how, what, and why WWC work is pursued. Additionally, the relationship is likely to be multilateral; for example, the increased use of cloud storage servers within the enterprise may raise questions of energy consumption and carbon emissions. Conversely, future data centers or other important computing infrastructure may need to be located so as to minimize the potential impact of disruptive weather events. If the WWC enterprise invests in more modern computing capacities such as the cloud, it must ensure that the infrastructure to support these systems remain sustainable in the face of climate change risks and hazards.

4) Next steps for AMS

Building on a 2019 workshop discussing gaps between educational curricula and industry needs, AMS established an ad hoc Mind the Gap Committee in 2020 tasked with improving the alignment between the existing education system and early career workforce skills. In addition to supporting the work of the committee, the AMS Policy Program will continue to conduct workforce-based studies to further improve understanding of enterprise needs with the aim of effectively meeting current and future workforce challenges. One forthcoming study, currently in development, is likely to examine the stages of the enterprise pipeline in more detail. Additionally, AMS has been awarded an AIP Venture Fund Grant aimed at establishing a Career Counseling Portal to help its members be better prepared and more successful at securing employment in WWC fields.

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Appendix: Workshop Information

Discussion: Basic and Applied Research
Date: February 22, 2021, 2-4pm ET
Participant List:

- Dr. Amy McGovern: Professor, University of Oklahoma; Principal Investigator, NSF AI Institute for Research on Trustworthy AI in Weather, Climate, and Coastal Oceanography
- Laura Carriere: Center for Climate Simulation Lead, NASA
- Dr. Sue Ellen Haupt: Senior Scientist and Deputy Director of the Research Applications Laboratory, NCAR
- Dr. Andrea Lang: Associate Professor of Atmospheric & Environmental Sciences, University at Albany
- Dr. Maria Molina: Project Scientist with the Climate and Global Dynamics Laboratory, NCAR
- Dr. Daniel Rothenberg: Chief Scientist, ClimaCell
- Dr. Julie Pullen: Director of Product, Jupiter Intelligence
- Dr. Eva Zanzerkia: Program Director, National Science Foundation

Discussion: Hardware/Instrumentation/Cloud/HPC
Date: Wednesday, February 24, 2021, 2-4pm ET
Participant List:

- Dr. Sara Tucker: Staff Consultant Lidar Systems Engineer, Ball Aerospace and Technology
- Dr. Peter Neilley: Senior VP Global Forecasting Sciences, The Weather Company, IBM
- Irfan Elahi: Director of High Performance Computing Division, NCAR
- Dr. Ilene Carpenter: Earth Sciences Segment Manager, Hewlett Packard
- Chris Vagasky: Lightning Applications Manager, Vaisala
- Dr. Mitch Goldberg: Senior Scientist, NESDIS/NOAA
- Dr. Brian Etherton: Numerical Weather Prediction Scientist, Maxar Technologies
- Dr. Milan Curcic: Assistant Scientist, University of Miami; Co-founder, Cloudrun.co and Fortran-lang.org
- Anne Connor: Principle, Strategy, and Business Development, L3Harris Technologies
- Dr. Kim Whitehall: Senior Data and Applied Scientist, Microsoft
- Dr. Dallas Masters: Director, Earth Observations/GNSS, Spire Global
- Dr. Dylan Powell: Lockheed Martin Space
- Mark Hoekzema, Director of Meteorological Operations and Chief Meteorologist, Earth Networks

Discussion: Science Communication
Date: Friday, February 26, 2021, 2-4pm ET
Participant List:

- Greg Fishel: Broadcast Meteorologist; AMS CBM

- Dr. Victor Gensini: Associate Professor, Northern Illinois University; Deputy Director, NIU Center for Research Computing and Data; AMS CCM
- Dr. Alicia Wasula: President, Shade Tree Meteorology; AMS CCM
- David Dillahunt: Meteorologist, Southwest Airlines
- Jared Rennie: Research Associate, Cooperative Institute for Climate and Satellites- North Carolina; Research Meteorologist, Rennie Weather; AMS CCM
- Bernadette Woods Placky: Chief Meteorologist and Climate Matters Program Director, Climate Central; AMS CBM
- Dr. Sarvesh Garimella: Chief Scientist and Chief Operating Officer, My Radar/ACME AtronOmatic
- Ava Marie: Broadcast Meteorologist, WBAL; AMS CBM

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