

Report to NSF on AGU community recommendations and ideas regarding implementing Climate Change Solutions

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Abstract

Several bills moving through Congress are likely to provide significant funding for expanding research and results in climate change solutions (CCS). This is also a priority of the Biden-Harris Administration. The National Science Foundation (NSF) will be expected to distribute and manage much of this funding through its grant processes. Effective solutions require both a continuation and expansion of research on climate change—to understand and thus plan for potential impacts locally to globally and to continually assess solutions against a changing climate—and rapid adoption and implementation of this science with society at all levels. NSF asked AGU to convene its community to help provide guidance and recommendations for enabling significant and impactful CCS outcomes by 1 June. AGU was asked in particular to address the following: 1. Identify the biggest, more important interdisciplinary/convergent challenges in climate change that can be addressed in the next 2 to 3 years 2. Create 2-year and 3-year roadmaps to address the identified challenges. Indicate partnerships required to deliver on the promise. 3. Provide ideas on the creation of an aggressive outreach/communications plan to inform the public and decision makers on the critical importance of geoscience. 4. Identify information, training, and other resources needed to embed a culture of innovation, entrepreneurialism, and translational research in the geosciences. Given the short time frame for this report, AGU reached out to key leaders, including Council members, members of several committees, journal editors, early career scientists, and also included additional stakeholders from sectors relevant to CCS, including community leaders, planners and architects, business leaders, NGO representatives, and others. Participants were provided a form to submit ideas, and also invited to two workshops. The first was aimed at ideation around broad efforts and activities needed for impactful CCS; the second was aimed at in depth development of several broad efforts at scale. Overall, about 125 people participated; 78 responded to the survey, 82 attended the first workshop, and 28 attended the more-focused second workshop (see contributor list). This report provides a high-level summary of these inputs and recommendations, focusing on guiding principles and several ideas that received broader support at the workshops and post-workshop review. These guiding principles and ideas cover a range of activities and were viewed as having high importance for realizing impactful CCS at the scale of funding anticipated. These cover the major areas of the charge, including research and solutions, education, communication, and training. The participants and full list of ideas and suggestions are provided as an appendix. Many contributed directly to this report; the listed authors are the steering committee.

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Introduction

Several bills moving through Congress are likely to provide significant funding for expanding research and results in climate change solutions (CCS). This is also a priority of the Biden-Harris Administration. The National Science Foundation (NSF) will be expected to distribute and manage much of this funding through its grant processes. Effective solutions require both a continuation and expansion of research on climate change--to understand and thus plan for potential impacts locally to globally and to continually assess solutions against a changing climate--and rapid adoption and implementation of this science with society at all levels. NSF asked AGU to convene its community to help provide guidance and recommendations for enabling significant and impactful CCS outcomes by 1 June. AGU was asked in particular to address the following:

1. Identify the biggest, more important interdisciplinary/convergent challenges in climate change that can be addressed in the next 2 to 3 years
2. Create 2-year and 3-year roadmaps to address the identified challenges. Indicate partnerships required to deliver on the promise.
3. Provide ideas on the creation of an aggressive outreach/communications plan to inform the public and decision makers on the critical importance of geoscience.
4. Identify information, training, and other resources needed to embed a culture of innovation, entrepreneurialism, and translational research in the geosciences.

Given the short time frame for this report, AGU reached out to key leaders, including Council members, members of several committees, journal editors, early career scientists, and also included additional stakeholders from sectors relevant to CCS, including community leaders, planners and architects, business leaders, NGO representatives, and others. Participants were provided a form to submit ideas, and also invited to two workshops. The first was aimed at ideation around broad efforts and activities needed for impactful CCS; the second was aimed at in depth development of several broad efforts at scale. Overall, about 125 people participated; 78 responded to the survey, 82 attended the first workshop, and 28 attended the more-focused second workshop (see contributor list).

This report provides a high-level summary of these inputs and recommendations, focusing on guiding principles and several ideas that received broader support at the workshops and post-workshop review. These guiding principles and ideas cover a range of activities and were viewed as having high importance for realizing impactful CCS at the scale of funding anticipated. These cover the major areas of the charge, including research and solutions,

education, communication, and training. The participants and full list of ideas and suggestions are provided as an appendix.

Our focus is on integrative ideas that would provide for significant impacts in 2-3 years in climate change solutions, as requested in the charge. As a result, important topics that still need considerable research efforts, such as exploring carbon capture and sequestration at scale, evaluating geoengineering, and developing sustainability or better management around critical resources including for key elements needed for future economies (among many others), are not included specifically but are important in addressing or could and should be included in some of these integrative efforts.

Funding and Program Guiding Principles

Addressing climate change is one of the major challenges facing humanity today. In addition to international political leadership, addressing it will require a major, rapid change in global energy usage and supply, as well as adaptation, mitigation, restoration, sequestration, and changes in human activities and planning at all levels, from small communities to international collaboratives. Climate change is intimately connected to other needs and services such as for clean water and air, food, and health, and is exacerbating inequity and the impacts of poverty and lack of resources. Often the communities and countries most in need of CCS are least able to have access to resources and expertise.

For the most part, programs in CCS have not been a key focus of NSF and other funding agencies. While the bills moving through Congress will address this major problem in terms of financial support, it means that NSF will need to rapidly add this capacity and capability (1) internally as well as (2) in the design of external grant programs to have immediate impacts. Significant efforts in both are needed commensurate with the scale of funding expected.

Recommendations and feedback provided by the AGU community address both of these challenges. At the highest level, several key themes, or guiding principles, emerged across the brainstorming and input provided by participants and stakeholders that apply to both internal and external challenges. These principles represent universal needs for this effort to be successful that must be explicitly and intentionally included and addressed in any main grant program or activity. The collective view is that programs, activities, and initiatives that start from these principles and goals and incorporate them broadly will have the greatest chance of success. These are:

1. The importance of the Earth and space sciences in this effort.

The Earth and space sciences are essential for successful CCS at all scales and need to be incorporated with CCS efforts in other NSF program areas. This science includes and forms the basis for our current understanding of climate change and impacts. The science covers

all environmental data collection and risk and impact assessments needed for informed decisions and ongoing assessments, and modeling that provides for future planning. It is essential input for addressing future risks, consequences, capacity, and planning for solutions at all scales for communities, businesses, governments, and any stakeholder, and provides perspectives and lessons from past efforts, and from understanding the past history of environmental change on Earth. Many Earth and space scientists are engaged with communities in providing advice and solutions directly, including some disadvantaged communities. We thus collectively hope that NSF leadership sees the obvious need for full integration and support of the Earth and space sciences, mostly included in the GEO program, in its CCS efforts.

2. Build off of, leverage, and connect existing programs in and associated with Geo Directorate and guidance, particularly Earth in Time:

<https://www.nap.edu/read/25761/chapter/1>.

Many current programs and initiatives underway at NSF can be expanded and leveraged to support CCS; some are explicitly listed in the appendix. Many programs support Earth observations, observational networks, and data (e.g. NEON, CZO's, BCODMO, UNAVCO, and other repositories), while many others are supporting climate-related research, and climate equity. All can be expanded or extended to address CCS by implementing some of the goals and objectives outlined here. Expanding from existing programs, as appropriate, may allow a more nimble approach and speedier results to obtain significant solutions within 2-3 years. Given the scale of funding and the transdisciplinary requirements for CCS, NSF may also want to consider developing an integrative program (see below). Overall, many of these efforts align with and enable the first seven of the ten NSF big ideas:

https://www.nsf.gov/news/special_reports/big_ideas/

3. Incentivize and develop new partnerships broadly including: across NSF, with other agencies, and externally; and with communities at all levels. This includes incentivizing co-creation of research and solutions with partners and communities.

Supporting CCS work requires transdisciplinary research and engagement in ways that NSF or few other federal agencies have done or done well. This will require NSF to develop stronger partnerships internally, with other agencies, and especially with external partners. A particular need will be how to meaningfully engage community leaders and organizers at a variety of scales, and especially in disadvantaged communities, in the grant and proposal process and in CCS work developed through NSF grants. Many of the needed partners are not familiar with the grant process and do not have a support network to participate easily let alone register for or administer grants. On the other hand, NSF can more directly incentivize potential awardees (researchers and their institutions) to engage in outreach

and transdisciplinary research through the grant process and demonstrate collaboration and co-creation. This challenge extends to all the ideas below.

Internally, there are already some examples of interdisciplinary programs within NSF that can be considered as possible models, and one idea below develops this approach specifically. Climate change solutions touch many of the divisions and programs within NSF. Most other funding agencies (e.g., NOAA, NASA, NIH, EPA, DOI, USDA, DOA, DOE, NIEHS...) are logical partners to develop programs around CCS, especially those agencies already working on integrating research into applications. Another partner may be the interagency U.S. Global Change Research Program which is charged with developing federal research assessments and agendas on climate science, impacts, and resilience. A recent National Academies [report](#) outlined an integrated research agenda for the USGCRP to leverage in their strategic planning process. An example of a convergent topical idea (described further below) addresses the large challenge of climate change and human health. Separately, there has been a broad community effort to encourage HHS to develop a program in geohealth (<https://climatehealthaction.org/cta/climate-health-hhs-recommendations/>), and coordination is essential. Fostering this interagency awareness and coordination is imperative.

Externally, NSF should design research grants and other funding programs to incentivize meaningful engagement of partners and stakeholders with awardees and to promote transdisciplinary research that blends science, technology, and related fields for CCS, providing incentives for innovative partnerships. These may be business or industry partners, community and civic groups, or political entities. It will be important to ensure that those partnerships reflect and advance goals around equity.

Research in community science has shown that the best outcomes and solutions occur when the partners are actively engaged and have a more equal role, or are equitably invested, in the outcomes. This means directing engagement beyond traditional “letters of support” so that partners are co-creators of the research proposal and treated as equals and major participants in the solution design and implementation throughout the project. Some of the most adventurous ways to encourage co-creation might be to support funding to community groups as part of or through the grant process and to provide or help develop resources, tools, or means to allow those groups ways to discover and select the scientists and scientific institutions with whom they want to work. While NSF may not be able to offer grants directly to community groups easily, or many groups may have severe difficulty applying, NSF may be able to support community participation in science by building partnerships with funders who can fund community groups, encouraging subcontracts from NSF-fundees for community partners, providing pass-through funding to other organizations that can manage community focused grants, or funding exploratory grants that position scientists and community groups to get additional funding from other sources. It's also important to develop the capacity to do effective boundary work within academic institutions, and these approaches will help.

Finally, NSF should support the science of community science, and development of a community of practice, to build and test many collaborative models for change that unite around science, research, and community.

4. Promote and implement equity and climate justice holistically and intentionally.

Climate change is exacerbating inequality globally. Meaningful CCS are in many cases most needed and will be most impactful in disadvantaged communities. It also requires a continuing evolution of scientific culture and practice so that people from diverse backgrounds feel welcome to “bring their whole selves” to this work. This requires meaningful collaboration and co-creation to build trust. Learning to work in partnership with Indigenous, Black, and Hispanic communities, and honoring those communities’ histories of scientific inquiry and learning from their traditions of equitable practice, will bring new approaches, knowledge, and ideas into the practice of science; expand and deepen the reach of science; and help science learn and adopt more equitable and just ways of working. Climate equity--ensuring all people have the opportunity to participate and benefit from climate science--is also part of the moral responsibility that accompanies the privileged position science and scientists hold. In addition, broader engagement with students and other members of these communities is essential to expanding diversity and inclusivity in the Earth and space sciences, and in all the sciences. All these challenges also point to the need for science at the intersection of social and environmental justice, equity, and inclusion. The urgency of climate change means that engagement and building trust has to occur while solutions are found, implemented, and continually assessed (e.g., see discussion on a fair and equitable transition to net-zero carbon emissions from the National Academy of Sciences [here](#)).

In the U.S., many of these communities are most connected with community and Tribal Colleges, historically Black colleges and universities (HBCUs), and Hispanic serving institutions (HSIs). Additionally, many of these institutions are experienced practitioners of community-driven and co-created approaches to science. For these reasons, there was a broad agreement among participants and respondents that significant efforts and explicit direction for CCS solutions be in support of work for disadvantaged communities and be directed toward community and Tribal Colleges, HSIs, and HBCUs, and that each larger program proposal and activity thoughtfully include climate equity in the design. In many activities this would mean that a certain proportion or amount of funding and support is intentionally directed toward this goal and towards those institutions. To be effective, many institutions will also need help and support in implementing leading practices around CCS through strong and continued engagement, connections, and liaisons with the broader community, and these will need to be developed and supported.

5. Develop skills for CCS and engagement across the Earth and space science community, and broader awareness of CCS overall.

Education and training of the Earth and space science workforce in CCS practices, cultural competency, and community engagement can have both immediate and long-term benefits. Long-term benefits are provided by a growing workforce supporting CCS and co-creation and engagement with all communities. Several of the major ideas below address this as do a number of individual ideas. This education can and should be through (1) traditional undergraduate and graduate curricula, (2) additional training, and (3) hands-on work. All are valuable and NSF should incentivize all. Several of the large ideas cover this space robustly. For all three areas, NSF can leverage tools and knowledge already developed by the many groups that have been practicing community science. Support is needed for this training and elevating and organizing the community of practice to help inform it. Knowledge of CCS is needed throughout STEM education.

These activities, especially the hands-on work, directly support communication around climate change. In particular, they build and engender mutual support and trust between science and scientists, and society and communities in ways that are not supported well by other science communication efforts that are mostly focused on one-way information delivery. Several of the ideas leverage this set of more innovative and amplifying approaches of knowledge exchange.

6. Lead a broader change in culture in the Earth and space sciences to support and realistically incentivize CCS.

The above guiding principles and themes collectively call for a culture change within the Earth and space sciences and academia in support of CCS work. Broadly, the practice of science should recognize, reward, and incentivize work with communities on CCS and on addressing climate change equity. Government, university and other leaders need to reform their environments to bring in diverse staff through an equitable process, implement true mentoring programs, and create an equitable environment for those hires to stay (from students to faculty to staff and administrators). Open science and expanding accessible and interoperable data needs true support. While these larger goals are beyond the specific remit of NSF alone, there are specific actions and steps that NSF could take that would clearly support and incentivize these goals, signal their importance, and also strengthen the proposals toward CCS.

NSF in particular could use this opportunity to support more directly (and direct behavior around) open data, community engagement, work in climate justice and equity through grant requirements.

One example might be how the “broader impacts” statement and criteria and Data Management Plans of grants are leveraged generally and specifically related to CCS. Currently these are valued differently, with different guidance, across NSF directorates and programs. A stronger intent seems to be aligned with the language in the NSF Authorization Bill approved by the House Science Committee. In most research grants, the “broader impact” statement is separate from the “intellectual merit” justification in grant proposals, and reviewers are asked to evaluate both. This can lead to the perception by awardees and reviewers that broader impacts are less important in the evaluation than knowledge creation or development of “new concepts.” The same is the case for the data management plan, which is one of the last sections of a proposal; availability and interoperability of environmental data and model results on the long-term are critical for implementing effective CCS and these require deliberate and strong data management. One approach to elevating these would be to combine these three parts together so that the primary justification in CCS proposals is jointly aimed at, “...explaining how the outcomes of this work—including new data, software, materials, samples, and products—will have scientific and societal value and impact.” This statement could reference the “broader impacts” statement directly if it was necessary to keep it, and the statement could also indicate how these “...outcomes will be shared rapidly or immediately using leading practices, referencing the DMP.” A stronger addition would be to ask how the outcomes are “scalable and adaptable.” This would elevate the broader impacts and data management efforts into the single core criteria of the proposal. In addition, expanding the pool of peer-reviewers to include non-scientists with expertise in community engagement and community leaders who have participated in collaborative science work could help elevate the attention to and quality and integration of community engagement in proposals. Similarly, including data managers as a requirement in generating the DMP, and in the proposal review, and/or directing use and engagement of certain repositories, would ensure that leading practices are followed.

NSF can also incentivize co-creation of CCS work by communities and work in disadvantaged communities as part of its programs and proposal calls. Certain proposal tracks could have these as requirements, including for some or all the work. Another idea is to prioritize proposals for engaging with communities. Incentivizing engagement and work with communities, sharing that work, and skills development by researchers would help lead this cultural change and signal its importance to other stakeholders, such as universities. Finally, sustained investment in community colleges, HBCUs, Tribal Colleges and HSI’s would allow those institutions to overcome decades of under-investment, buttress their ability to serve their historically underserved communities, and, because these institutions are often already leaders in co-creation, advance the co-created approaches and methods that will be essential to climate solutions.

Major Ideas

Engagement with the AGU community led to a wide range of ideas and activities that NSF could implement to develop meaningful impacts in CCS. All are included in the appendix documents. At the scale of funding expected, however, several ideas emerged as having potentially broad impacts and incorporate many or all the principles above. These major ideas also include many of the individual ideas. These are:

- Establish an Office of Climate Change Solutions at NSF
- Develop a Science/Climate Corps and Community Engagement Program
- Enable climate change solutions infrastructure through global environmental monitoring, data interoperability, and other major research equipment needs.
- Develop a funding program in GeoHealth, as a model for other transdisciplinary research
- Develop Regional Centers for Applied Science of Climate Adaptation
- Expand and rework Graduate Fellowships for Climate Change Solutions
- Develop broad-based research to anticipate surprises, assessing risks and identifying early warnings of rare but highly impactful events

These collectively are illustrative of major activities that would address most or all of the goals in NSF's charge--from supporting and fostering transdisciplinary research and CCS topics to skills development and training for the workforce and students, to education in CCS, to forming new and powerful means to improve communication and trust in climate science. Although these are discussed below separately, these ideas are highly symbiotic and overlap such that they could, or should, be developed together and interactively for much greater impact. They are not presented in order of priority in any way. The sense was that they covered the range of impacts NSF was seeking and are most impactful in combination, not that one or another was a higher priority.

Given the short time frame, many of these ideas and recommendations are incomplete with respect to a full roadmap and governance. If NSF is interested in further development and suggestions around these, many of those that have participated would be available to provide additional development.

Although not always stated, the notion was that the above principles should be thoughtfully included in these activities.

An Office of Climate Change Solutions at NSF

Providing for CCS and managing a program at the scale of \$2billion/year is a huge transdisciplinary project and needs coordination and interaction across many involved

parties, institutions, and stakeholders, especially from disadvantaged, vulnerable communities. At NSF, coordination will be needed across most divisions and initiatives, from social science, education, engineering, computational science, major infrastructure, to the geosciences. A suitable cross-cutting unit at NSF needs to be tasked with making this coordination and standardization happen. It would be able to set up one coherent set of expectations for CCS across all initiatives and programs (including strategic goals, reporting requirements). We have outlined above some of the principles and priorities that we believe should be included in such a coherent CCS vision.

A new transdisciplinary office will be more resilient to future potential reorganization and maintain stable, sustained funding over the course of future administration changes. Transdisciplinary research and education have distinct needs in regards to support, language, programming, and social equity goals, and a transdisciplinary office within NSF will be in a better position to address these needs. In addition, such an office would:

- Establish a co-funding policy for CCS research, engagement, training, with 20% incremental funding to relevant programs and initiatives across the entirety of NSF portfolio, prioritizing those which relate to the needs of disadvantaged, vulnerable communities. (~\$1B/yr)
- Establish a core CCS program at NSF with suitable funding, embedded within a transdisciplinary office. (~\$100M/yr)
- Dedicate funding for high impact infrastructure investments strongly linked to CCS research within NSF (such as greatly increasing funding for CCS related computing (at NCAR or XSEDE) or for research vessels, observatories, or research stations). (~\$500M/yr)
- Dedicate seed, matching and co-funding for high impact (in particular for disadvantaged communities), transdisciplinary CCS efforts for collaborations beyond NSF (including other federal agencies, NGOs, other private and public sector organizations at ~\$500M/yr).
- Signal the importance of CCS and transdisciplinary and co-created work, especially with under-represented groups.
- Signal the importance of equity and justice in CCS programs
- Support and coordinate all the other initiatives related to CCS; ensuring focus and enhancing accountability
- Support transparency around the efficacy of carbon removal technologies and monitoring data, which are currently being driven by the private sector and are thus less subject to peer review
- Support a sustainable FAIR repository ecosystem ([European Commission, 2018](#)) to enable interoperability of data and repositories funded across separate directorates needed for CCS.
- Create space for novel transdisciplinary discovery and scientific advancements.
- Support common education/training, community engagement, and FAIR data practices, and extend leading practices across NSF.

- Reduce barriers to cross program and cross institution funding.
- Support universities and other organizations that are working across silos to advance climate solutions across multiple disciplines, schools, departments, etc. with special consideration of HBCUs and Tribal Colleges.
- Coordinate linkages between research institutions, community partners, and businesses to facilitate partnership and speed up implementation.
- Develop programming that intentionally explores the overlapping space between institutional turf - for example, work on the common ground between NSF, NIH, and CDC to focus on public health programming, or work on the common ground between NSF and many other USGCRP agencies to focus on community climate adaptation.
- Create roadmaps and opportunities that allow student groups, community groups, and nonprofit groups to participate in these grants (including application workshops, directed outreach efforts, and promise for administrative support), in particular for those from disadvantaged, vulnerable, and BIPOC communities.
- Foster expertise and guidance to review transdisciplinary proposals and cultivate overlapping areas of interest (e.g., climate and health).
- Ensure that significant support is provided to HBCUs, Tribal Colleges, and HSIs.

Such an administrative center would enable the pivot of a significant fraction of NSF (across all relevant directorates) toward Climate Change Solution-oriented science. This effort would allow for synergistic interactions at the margins between agencies (such as NSF and NIH, NOAA, NASA, DOI, USDA). It would support and signal that transdisciplinary and community engaged proposals would be a priority.

Science Corps and Community Engagement Program

The Science Corps (tentative name for this proposal--see below) is a fellowship that places science ambassadors in communities to help those communities advance their priorities in ways that leverage existing and emergent climate science and inform future climate research. For example, the work might be less about convincing communities to add climate change adaptation and resilience to an already crowded list of to-dos, but it may be about using climate resilience and sustainability to help communities tackle existing to-do lists. For example, a community may be focused on affordable housing, and the Science Corps might help design housing that is as affordable in the long term (i.e., sustainable, resilient, net-zero) as well as the short term. How to do that would promote near-term action and generate new research questions.

The Corps will rely on, draw from, and help communities connect to the broad landscape of federal resources, including but not limited to NSF research centers and activities. One way to think of it is that the Corps can help communities navigate the myriad of centers, tools and services - the Corps provides a “no wrong door” entry to climate resilience and mitigation.

The Corps will center equity and justice. It should focus its efforts on historically marginalized communities and communities that are most vulnerable to climate change; Corps members should come predominantly from groups that have been historically under-represented in science; and the program leadership and direction should draw from and support community-embedded institutions and institutions with long track records of community engagement, especially Tribal Colleges, HBCUs, and HSIs.

Implementing CCS globally requires direct engagement with communities, especially climate-vulnerable and historically marginalized communities, and working with them as partners. Such an engagement has many downstream benefits--it engenders trust in and support for science and opens broader communication and engagement opportunities. For scientists, it creates a growing community of practice around community science and provides ideas for future research directions that more directly connect to climate solutions. This also serves to train a growing workforce with skills in community partnerships and in applying science to real-world decision making. It can help the lack of diversity in science and help ensure the priorities of communities of color guide scientific research. Current community science programs, many led out of minority serving institutions, have developed the knowledge and expertise for such engagement but have not been supported to the extent where their work can scale. There are also few opportunities to link these mostly disparate efforts to share what works.

Developing a climate-focused science Corps program at NSF could thus have a significant lasting and amplifying impact. An approximately 5,000-member (in 3 years) community-focused Corps would lead to concrete action in climate adaptation and mitigation in communities of color, rural communities, Indigenous communities, and climate-vulnerable communities while also developing the future workforce for a sustained effort around CCS. In detail, it would provide paid professional experience for both early career and professionals with science backgrounds to work directly with communities. This Corps could take a variety of forms, but at its core, it would support a strong network of members—the majority recruited from communities currently under-represented in science, who would acquire and build expertise in climate science and community engagement through connections with educational and research institutions, federally-supported climate centers, and climate adaptation efforts already underway. The program would focus on providing strong mentorship opportunities, peer-to-peer support, opportunities for graduate work, and evaluation that promote early successes and allow for more rapid scaling of solutions. One possible model would be a 2-year residence, where Corps members would work directly within a community organization. Another model would be a job retooling fellowship, where Corps members would stay within their existing organization but would be supported (given time and training) to work on climate solutions. Another model would be students (in community colleges or graduate programs) being supported to do work within a community as part of their studies (splitting time between classes and community engagement, with the collective work supporting degree

requirements). Yet another model would support local leaders to engage in climate solutions thinking, ensuring knowledge and connections stay within the community for decades to come. Ideally these different program models would be in place simultaneously, encouraging cross pollination as well as innovations and learning (including research) on what program models are most effective.

If started immediately, as an illustration of potential impact, in 3 years 5,000 communities will have advanced adaptation and resilience; 5,000 scientists will have improved collaborative skills. It would also develop good, shareable ideas and reveal future research directions informed and driven by emergent needs. The disparity in who has access to climate science will be lessened. 5,000 alumni and the communities they have served would become a powerful force for culture change.

This also addresses CCS at the source: Many communities lack information and knowledge about how to use climate science to advance adaptation, restoration, and mitigation or how to translate science into action. There are two problems here--not knowing where to find reliable information or service, or being overwhelmed by the choices available. The Corps could help both, by learning about the community and helping them connect to the most relevant and appropriate resources and centers for that community. The Corps, in this way, could magnify the impact of existing climate centers from across the federal agencies, by serving as a broker between communities and those centers. This also provides an opportunity to learn more quickly what resources have greatest value and could possibly scale up. This effort would build the knowledge while also building broad trust and support in science, and provide for deep communication with the public around CCS.

In particular, a Science Corps could be designed to:

- Provide on-the-job training and community building opportunities in co-production for scientists and community members.
- Allow placement of Corps members in communities guided by equity considerations.
- Prioritize recruitment of Corps members from minoritized communities or at/with minority serving institutions.
- Support and enable use of FAIR data and tools by communities.
- Provide local leaders with scientific resources and expertise to take advantage of and help develop climate solutions.
- Provide training for Corps members and the teams they work with, all of which pulls from previous NSF investments.

Other recommendations included:

- The Corps should prioritize placement within frontline communities, communities that have or are experiencing environmental injustice, rural and isolated

communities, and communities who have been denied opportunities to generate wealth and power through racist or colonial policies.

- Provide Corps members salaries and funds for projects that can attract professionals (not just early career, not just for those wanting to do a community service endeavor).
- Encourage applicants at all career stages - avenues for students, undergrads, pre-college, community colleges, professionals who want to change careers - and create a strong network of mutual support, and peer-mentoring.
- Focus on opportunities for Corps members who come from groups that have been historically under-represented in science.
- Allow opportunities to participate at multiple time-commitment levels - from something you do while in graduate school to a full-time engagement.
- Implement cross-career stage and cross-expertise teams paired with a group of communities to allow flexibility and testing of different approaches (and study it, test: learning, attitudes, change outcomes).
- Teams could also be attached to/support existing multi-agency centers or regional centers (see below).
- This effort can be explicitly tied into the broader Biden administration's Civilian Climate Corps initiative, taking a leadership role on elements that engage in the science at universities, non-profits, and businesses.
- Have a low barrier for communities to seek/obtain the assistance of the Science Corps.
- Ensure that this Corps is supported with a strong network structure; include connections between cohorts etc.
- Build peer mentoring and alumni networks.
- The Corps should support and build on the cutting-edge community-based work at minority-serving institutions.
- Build in opportunities to test collaborative models that unite science, research, and community, including research positions in social, behavioral, and economic sciences and provide projects a means for evaluation.
- The name Science Corps (v. Climate Corps) could distinguish it from other proposed climate corps and emphasize NSF's science role and make it more accessible to all communities. Another consideration is that the Corps needs to be named in a thoughtful way - a "Science Corps" may not resonate with community groups or the professionals and students involved in the Corps.
- More generally, the name should also be carefully considered - Corps might be too closely aligned with other service experiences (existing e.g., AmeriCorps or Peace Corps, or new proposed early-career opportunities). Instead of Corps, perhaps its: community liaisons, ambassadors, officers, fellows, advocates, enthusiasts, coordinators, or champions (e.g., Community Science Coordinators).
- Connect with NSF Research Traineeship and Integrative Graduate Education and Research Traineeship (NRT/IGERT) programs.
- The Corps could provide opportunities to connect with K-12 education

To be successful quickly, this program should build on and work closely with existing efforts and boundary organizations with experience in supporting people to integrate climate science in policy and practice at all levels.

There are great opportunities to leverage existing resources for training and for mentoring and oversight. Models for this type of work are the AGU's Thriving Earth Exchange and the California Climate Action Corps (<https://www.californiavolunteers.ca.gov/climateactioncorps>).

A Suggested RoadMap:

Year One could focus on convening an advisory committee, building training and mentoring capacity, recruiting Science Corps members, identifying Science Corps communities, supporting an integrated formative evaluation capacity, and marshalling resources to support the Science Corps members and communities, including around additional training- or more broadly developing a community of practice. An advisory group would help set overall program goals and high-level policies and create a clear picture of program success to aspire to. For example, the advisory board could clarify that the program needs to prioritize work with minority and marginalized communities and engage Corps members from groups historically under-represented in science. NSF could solicit proposals to develop training materials and manage regional hubs that would train, mentor, and support area Science Corps members. As mentioned there are existing resources in the climate science and climate science communication community that could be leveraged, and strong nascent efforts that could step up to this larger role. It may make sense to situate the recruitment efforts within these training and mentoring hubs as well, but the recruitment efforts should be based on existing research and community knowledge about the characteristics of effective boundary spanners in the climate solutions space, and NSF may want to solicit a synthesis of such research to guide program activities. To recruit communities, the advisory committee could help establish clear goals for an inclusive geographic, demographic, socio-economic set of communities, and NSF could work with other federal agencies, NGOs, professional associations of local government leaders (like the International County Managers Association), and community organizers (e.g., healthequityguide.org) to reach local community leaders. It may be helpful to fund a national-scale effort to recruit into the program and help orient and onboard local leaders from those communities.

Since it will be vital that the Corps is connected to a rich body of datasets, tools, and services, NSF might solicit proposals for collating and offering those supports - the resource hubs may be attached to existing or proposed regional climate centers. Formative evaluation needs to be designed into the program, and NSF should identify and fund evaluators to design and carry out a comprehensive evaluation and work with the advisory board to ensure that evaluation findings flow back into program operations.

Finally, Year One needs to include setting aside financial resources to support proposals from the Corps communities and members, so that they can implement the projects that they design. By the end of the first year, it would be ideal if NSF were able to convene the advisory board, regional training hubs, supporting resource hubs, community recruiters and partner organizations, evaluation team and recruiting partners to level-set, build common vision, create peer-to-peer connections, and launch the program.

Year Two would focus on training and placing Corps members, building solid connections between those Corps members and local institutions, and having the Corps members work in their communities to co-design impactful locally focused projects that enhance climate readiness. Corps members will emerge from their training and engage in a 3-4 month period of listening and brainstorming - the goal would be to come to consensus on an impactful, catalytic community project that would advance local climate readiness using science.

The regional training hubs would support the Corps members as they develop these plans, advising on feasibility, troubleshooting issues, helping support community buy-in, etc. Local regional hubs would provide tools, data, and services necessary to help define and carry out the projects. By six months into this year, each community and their Corps member have co-developed a plan for carrying out their catalytic project, and those plans will trigger the release of funds to the community for carrying out those plans. At the end of year one, the regional training and mentoring hubs might convene or partner with an existing local event to enhance the peer-to-peer and community-to-community interaction, identify affinities and overarching themes that can guide program development and feed back to the overall program team, and build affinity groups around common interests or related projects.

Year Three would focus on completing local projects, helping Corps members transition to new opportunities, helping participating communities build on the catalytic projects, collecting and sharing successes, reflecting on lessons learned, and exploring options for continuing the program.

The most important goal of year three is the completion of the individual community projects and the ways in which those projects foster continued community engagement in climate solutions. The second overarching goal could focus on overall learning--what do the individual projects offer in terms of a catalogue of climate innovation (what can be scaled, what can be shared); what have we learned about collaborative approaches to climate science and how can that be incorporated into NSF programs, graduate education, regional climate centers, etc; and what have we learned about community priorities that can inform NSF's research agenda and practices. The final goal would be an overall assessment of the program's impact--what did it accomplish and how it could evolve. This should set the stage for a second, improved iteration of the program.

Global Environmental Monitoring, Data Interoperability, and Major Equipment for CCS

A major challenge for implementing CCS both in the near term and over decades is the critical need for rich, findable, accessible, interoperable, and reusable (FAIR) data--both for environmental monitoring but also for informed decisions by planners, communities, and governments. For example, reducing emissions may require real-time and continuous measurement of greenhouse gases across a region at a scale that can identify sources and be combined with Lagrangian atmospheric models or downcast climate model output and a variety of socioeconomic data. Environmental data will need to be combined with each other, and agricultural, public health, and social-economic data for land use decisions. Measurements will need to be interoperable across regions. A variety of new sensors, including those that can be enabled by community scientists, are becoming available. Deploying these, creating interoperability and standards, and engaging communities in making use of the available data are essential for impactful CCS. The economic benefits from better decisions and informed mitigation, restoration, and adaptation are huge. Such data would also support a wide range of longitudinal research on Earth's climate and environmental systems. Support is needed for continuous/real time data as well as more detailed interoperable data on individual systems spanning ecological and environmental systems.

Climate data and measurements are also needed from remote regions--the Arctic, Antarctic, and deep ocean are particularly lacking yet key areas for understanding the climate system, improving models, and understanding risks and tipping points. Collecting rich data from these regions requires larger infrastructure investments including in ice breakers (the current US ship is obsolete), ocean remote sensors, drones, remote data collection centers and more.

Effective data management, ongoing curation efforts and adjustments of data services to meet changing user needs are critical for empowering this essential data. This requires sustained support for repositories and data services. Such repository support has overall been lacking; many are on short-term funding where much of their resources are spent securing additional funding.

Currently these efforts are distributed across NSF and primarily driven by separate directorates based on individual and historic research needs and communities. CCS requires integration of data and broad training both of data creators and users (including public), co-creation of relevant data, co-use and overall a more directed effort. Thus elevating this effort would be extremely impactful.

Some other considerations and needs are:

- Can leverage existing NSF efforts such as NEON, CZO's, and other external efforts like the [GEMM](#) initiative.
- International coordination in building a FAIR ecosystem is critical.
- There is need for training and support for interoperability/curation, and public education opportunities w/ data streams.
- Incentivize data collection in disadvantaged communities, including to understand the proportional impacts of climate change and potential benefits of CCS.
- Support equitable development of citizen/community data collection and sharing.
- Co-develop processes with indigenous communities that honors and implements indigenous data sovereignty as described in the [CARE Data Principles](#) that bring an equitable, human perspective to open data governance.
- Monetary support for development and maintenance of "learning parks:" Earth surface process learning sandboxes that are maintained adjacent / integrated with playgrounds and parks for natural and intuitive learning / education of the public.
- Can enable or incentivize learning parks, and interoperability hackathons to incentivize co-creation of the data and ensure data reusability.
- Support funding and access to climate data and climate modeling for climate intervention/climate restoration solutions - both for small-scale field testing and monitoring of any unintended consequences.
- Support international collaborations for monitoring, data sharing, intercomparison across sensor networks.
- Support and fund development of policy/governance frameworks for climate interventional solutions.
- Support calls for and development of appropriate sensors and data collection for important data monitoring for climate change, water supply, health concerns.
- Focus on the extreme and leveraged importance of polar regions for climate change overall. Increase access to climate modeling and data repositories to increase learning about what possible actions could have beneficial impacts - and what the risks from such interventions could be.
- Increased collaboration between climate modeling and insurance industry to surface risks and costs of not doing any interventions or CCS.
- Support repository infrastructure (for domain repositories) as an essential building block of a FAIR ecosystem for this effort across agencies.
- Support data usage/traceability methods to enhance transparency and trust in derived datasets
- Train data management expertise/curators. This is needed broadly to enable FAIR data, help researchers, and manage expected data volumes. These can also provide data services for CCS, and expand capacity building for data management and co-creation for members from underrepresented groups/disadvantaged communities.
- Development of tools for citizens (apps or sensors for data collection).
- Work across fields for data management, curation, and services which need to be coordinated across agencies and data providers including internationally and economic, health, and social data. The ideal goal is an infrastructure/data service

that allows easy discovery and reuse of CCS-relevant data for different data user groups (e.g., no data hunting across different repositories and reduces the effort that users need to wrangle the data).

Climate Change and Health, and more broadly, GeoHealth

One of the most critical areas where CCS are needed, and an area with relatively poor funding and support, is climate change and health. Health here includes human health, as well as the health of marine and terrestrial ecosystems, agricultural systems, and planetary-scale systems on which humans depend. Climate change has many direct and indirect effects on health ([USGCRP 2016](#)). The World Health Organization lists emissions and related air pollution as the top leading global health challenges. Adverse health effects are intimately related to and caused by climate change and often have a cascading impact with existing risks--from heat stress to risks to the food and clean water supplies, to climate-change induced migrations and ecosystem collapse. The impacts of climate change do not affect all equally and often those already marginalized populations will be more vulnerable to adverse health consequences from a changing climate, both globally and domestically. The multifaceted challenges of climate change and health are a seminal demonstration of the cross-discipline, cross-community, and, from a funding perspective, cross-agency nature of geohealth sciences. From both research and applications perspectives, geohealth problems involve complex interactions between natural and human systems that play out in diverse contexts and across a wide range of spatial and temporal scales.

For this reason, an NSF focus on geohealth would require and exemplify transdisciplinary science and community engagement and require partnerships with other agencies. It is critical that the Earth and space science community be engaged and play a leading role in this topic. Research and solutions related to climate change and health have been undersupported, there has been no sustained training funding for climate and health scientists and no supported career development pathway, and key communities are not strongly interacting and collaborating yet. The climate and health research done to date focuses more on harms than on solutions and there are no platforms that integrate Earth sciences into health surveillance activities and other forms of decision support.

These disconnects between research and solutions are, in part, symptoms of stovepiped funding jurisdictions: most notably, the fact that the NSF has invested in Earth and space science research while the National Institutes of Health has supported research on human health. The climate and health challenge, and geohealth more broadly, lies at the intersection of these traditional mandates. While individual programs at NSF have, at times, bridged this gap, and while other funding agencies have also engaged on targeted elements of geohealth science--for example, the NASA Health & Air Quality Program and the NOAA Climate Programs Office--there is an opportunity for NSF to lead discovery to solutions science in the realm of geohealth. The breadth of the NSF research portfolio and the agency's commitment to interdisciplinary and transdisciplinary analysis of complex systems put it in a uniquely powerful position to advance geohealth collaborations.

In addition, the health challenges of the climate crisis have taken new prominence from the lessons learned from the Covid-19 Pandemic, including lessons related to the drivers of disease emergence, the potential for rapid shifts in global health status, and the fundamental importance of functional health systems. Because of the high importance of health, the underdevelopment of climate and health as a field, and the great potential to leverage tools and collaborations involving Earth and other physical sciences, of the transdisciplinary and convergent topics, GeoHealth is a high priority to develop and could serve as an example of other such convergent initiatives.

Some activities could include:

- Traditional research awards that affect or understand health and economic outcomes related to climate change.
- Traditional research awards focused on identifying, evaluating, and implementing at scale solutions to reduce health risks associated with climate change.
- Develop systemic changes to the current funding model to more easily enable a multi-agency grant process for climate and health solutions and leverage interagency mechanisms like the USGCRP to inform a research strategy.
- Awards to support integration of Earth observations and data streams into public health risk assessment, surveillance, and practice at multiple scales, from local to regional to global ([Tong et al., 2021](#)).
- Awards to build communities of practice; fellowships and funds to support travel/collaboration and career development with opportunity for individuals to step into this space.
- Decision support centers: A concerted effort to produce decision support tools that easily translate or visualize integrated data for health decision makers domestically and globally. The community should be curating integrated data tools so health practitioners can make the needed decisions and track impacts more effectively. Similar to the National Weather Service and how weather forecasts are provided for day-to-day decisions (heat warning, air quality, fire forecasts, drought monitoring) but specific to climate-sensitive environmental exposures and related health risks. These centers could also serve as data archives and distribution centers.
- Perception of risk depends on lived-experiences and health is central to risk management. Fund partnerships, non-hierarchical for NGOs, centers of outreach e.g. museums/policy centers, and department/programs at institutions can connect and collaborate, listen to one another.
- Reserve specific grant amounts to historically marginalized communities (environmental justice) and prioritize academics that are transdisciplinary in nature, inclusive of the underrepresented, and focus on a co-production model of knowledge creation.
- There is a big training need. The climate and health field has been systematically starved from resources. Everyone has trained in an ad-hoc approach. A joint NSF-NIH training grant program with opportunities for trainees and investigators at

various career stages would be valuable (could be modeled after the NSF IA Institute initiative, which includes joint support from several agencies).

- Training for scientists at all levels to brief policy and decision makers.
- Incentivize transdisciplinary meetings, workshops, and connections in this space.
- Funding of rapid response research teams to respond to and learn from GeoHealth events.
- Traditional research awards that help us understand the mental health impacts of climate change, both for communities directly impacted by our changing climate and on the researchers studying the impacts, as well as understanding the positive mental health outcomes that the environment can have on individuals and communities.
- Traditional research awards to understand the cumulative impacts from environmental and societal stressors that are exacerbated by climate change.
- Partnerships with hospitals and other healthcare centers.
- Funding for regional communications - people care about and understand what is local to them (e.g. what does a changing climate look like in different parts of the country?).
- Climatic impacts on health are not limited by a geographical boundary; support is needed to study the public health issue related with climate change in other parts of the world through international collaboration, especially with resource-limited regions which are also typically regions with higher vulnerability to climate change caused public health issues. This could be coordinated with other agencies (e.g., NASA, NOAA, USAID, NIH).

Regional Centers for Building Climate Change Resilience and Solutions

Much CCS involves adaptation and mitigation at a local or regional scale, in part because the effects and impacts vary regionally. Many universities are also connected to their local and regional communities--including for and with students and their careers, business relationships, government leaders. Forming and fostering regional centers would address several critical CCS needs.

The Centers would represent rich cross-university linkages to leverage resources and break down institutional barriers to confront regional scale problems and solutions. They would bring together a full team of climate scientists, hydrologists, geomorphologists, ecologists, etc. and thereby exploit the broad expertise that can be gathered in a regional approach--not a Center led and populated by a single or just a few institutions or a single agency.

The Regional Centers would collect and organize a deep transdisciplinary bench of scientific horsepower that resides in academic institutions. They would be configured to provide the targeted attack on the most pressing problems facing regions. The proposed

Regional Centers would provide knowledge, tools, and a workforce for the established Federal Regional Centers, as well work with state agencies and local communities.

The Regional Centers would provide incentives, funding, and other resources intended to help scientists at diverse universities work together to solve these problems. As it currently stands, researchers at individual universities will pursue topics of interest which may have little application to the region in which they live. Regional Centers would provide an incentive for researchers to band together to tackle challenging problems of climate solutions. They could include and form an explicit collaborative structure around CCS for regional community and minority-serving colleges.

The Regional Centers would also enable the deep education and training of students needed to tackle the rich and complex problems of climate change. Here too, collective effort in education, instead of islands of instruction at various universities, can potentially lead to a powerful educational enterprise. Student training and community-based involvement and co-production can both be incentivized and included explicitly. This would also incentivize rethinking education around what it means to be a scientist on a changing planet and supporting new career trajectories. Summer training programs can bring modelers and field people together, and the Regional Centers could be combined with the climate corps program.

The Centers would form alliances and collaborations with agencies (city, county, state, federal), agriculture and resource industries, and non-profit organizations to identify needs and test methods for building resilience and solutions, and study implementation of measures motivated by Centers findings. The federal and state land management agencies that do not have capacity to develop this expertise on their own. The regional centers would truly be centers of convergence research. Economic, social, and cultural elements need to be integrated into Center research in order to address values, needs and equity and to implement successful actions. These Centers are focused on the science needed to build resilience and solutions- but applications would be accomplished by city, county, state, and federal agencies and nonprofits.

In the US, approximately 10 centers could be envisioned: Alaska, Hawaii/Puerto Rico, West Coast, Rocky Mountains, Upper Midwest, Northeast, Southeast, coastal (FL, NC, TX etc.), Southwest. NSF could start out with 2-3 as pilot sites. These centers would leverage other NSF efforts that have regional hubs or centers such as: CZO, LTER, NEON, “new Artic”, RCNs, STCs and would bridge relationships with DOE sites, USDA Climate Hubs, NOAA RISAs, etc. and importantly, also to state agencies--they are on the front line but have neither the staff nor the sufficient training to study mechanisms, monitor, and model.

These Centers would demonstrate and embody the importance of site-based science: system-level understanding and testable hypotheses that can be broadly applied, and

acquisition of long-term datasets to both document and understand changing processes and develop and test rigorous models of resilience.

The kinds of questions that would organize the work of these proposed Centers would be regionally specific, and would logically be developed in an open process that included a diverse set of scientists, community leaders, policy thinkers, politicians, NGOs, etc. As an example of the scale and scientific depth of these questions, here are some potential overarching (driving) questions and sub-question candidates from a West Coast (WA, OR, CA) Center:

1. How in the US West Coast will the regional climate, vegetation, and water resources co-evolve, and what will be the consequences for ecosystems, agriculture, hazards, and society?
2. What actions can be taken through land and water resource management and societal practices that will build resilience and contribute to climate solutions.
3. Is it possible to anticipate the magnitude (space extent and degree of drying), and importantly, duration of drought cycles?
4. Can we forecast major rainstorms (amount, intensity, and spatial extent) and how will these storms compare to the historical record?
5. What important teleconnections to drought cycles can be understood and addressed, such as Arctic ice melt affecting weather patterns resulting in more severe droughts and fire seasons in California?
6. How will topography and critical zone architecture influence the interplay between climate change and vegetation dynamics?
7. Can forest management in the Sierra offset fire threats and compensate for reduced snow accumulations? Can we build a resilient landscape to wildland fires and their consequences?
8. Will carbon sequestration in forests be effective over the long term?
9. What are Sea level rise consequences for the Sacramento delta... and so on
10. How can local agricultural systems change, e.g. wineries need to move north?, some crops not viable in the central valley?, exhaustion of mined groundwater in the Sacramento/San Joaquin valleys?
11. How can water be better managed?

These Centers would complement but are different from existing agency science centers (i.e., USDA Climate Hubs, DOE Science Centers, NOAA centers and so forth). These represent clear assets which any new center would need to develop strong linkages, they differ in a number of key respects: While they are organized to provide CCS, they are not typically (there may be exceptions) addressing the fundamental science questions that underlie regional-scale climate impacts and potential solutions. The best way to illustrate this gap is to consider how much these centers are enabling science focused on the fundamental climate change questions facing communities in specific regions. The Regional Centers we envision would be organized around these key questions.

The Regional Centers would seek the strong interaction across all pertinent disciplines including climate (NOAA), geology and hydrology (USGS), and agriculture (USDA). These centers would need to be established for a long period such that the diverse communities can learn to work together, challenge difficult problems, and can invest in long term monitoring (to document basic processes and functional changes in systems as the climate warms). Such Centers would reach across the NSF Directorates of Biology, Geoscience, Education, and Social, Behavioral and Economic Science, and by necessity require convergence science.

To support these, large amounts of small-scale funding could be made available for individual communities to collaborate with such centers.

Finally, these Regional Centers could or should leverage many of the other ideas here.

Expand Graduate Fellowships focusing on CCS

The graduate fellowship program is a key leverage point at NSF to incentivize CCS training and research and a broader cultural change in the sciences. For a modest amount (and thus a smaller investment than some of these other suggestions) NSF could expand these greatly and have a large immediate impact in CCS, training, career development, and send a strong signal to universities on the importance of CCS.

Some ways to incentive these further would be to:

- Award them by January in advance of graduate school selection.
- Include requirements for diversity in applicants and awards.
- Applicants should propose a major field of study of relevance to CCS.
- Can incentivize co-creation with communities or Science Corps participation, and climate equity in the proposals.
- Flexibility could be added for senior undergraduates and masters programs.
- Incentives could be provided through the design for considering or promoting work in areas disproportionately affected by climate change.
- Could be coordinated with regional centers or calls for specific transdisciplinary topics (cf. geohealth).

Develop broad-based research to anticipate surprises, assessing risks and identifying early warnings of rare but highly impactful events

Some of the highest risks associated with climate change, and ones that would affect all solutions are highly non-linear responses triggered by the increased accumulation of greenhouse gases in Earth's atmosphere. These rare but highly impactful events ("black swans", "tipping-point behaviors", "abrupt changes") can significantly affect or even

dominate risk profiles. Such events may occur in physical or biological systems, and especially in human systems. While there has been some research on these and these risks, for the most part the transdisciplinary research needed to incorporate these risks into solutions is very immature. Similarly the combined research and monitoring to assess these and their imminent likelihood is lacking. This effort would amplify and tie into most of the other efforts closely and also requires new transdisciplinary collaborations.

Ice-sheet collapse, for example, might more than double projected sea-level rise. Sea ice disappearance can increase the risks of methane release in the Arctic. Carbon release from cold soils or sea-floor sediments could notably amplify warming. Drought-enabled wildfires could trigger very rapid and widespread ecosystem replacement. Reorganization of ocean circulation, spread of oceanic dead zones, and other large surprises are possible based on current understanding.

Human systems may be especially vulnerable. Projections generally assume that we will meet challenges efficiently, mitigating and adapting in ways that minimize costs. While history is replete with examples of human problem-solving, on other occasions groups of people have instead resorted to armed conflict or mass migration. Such decisions involve issues of perceived equity and justice as well as environmental conditions. Impacts and risks can extend to food supply, ecosystems, health, as well as local to larger scale, societal collapse, and could affect and need to be considered in any mitigation. Indeed many of the lessons from the COVID pandemic are exactly in this arena, and reinforce the importance of preparedness.

Just as every commuter considers risks of catastrophic accidents as well as usual traffic delays, all of the elements discussed here should include efforts to anticipate surprises. This should include learning more accurately the likelihood of occurrence of previously proposed “tipping point” behaviors, and identifying any new ones, and searching for early-warning signs and possible adaptation or mitigation strategies. Because of the tight couplings of physical, biological, and human systems, coordination should be sought across all of the CCS activities to achieve these goals.

Key activities to address this challenge would include:

- Expanded environmental monitoring, particularly in areas that are undersampled, such as polar regions, the deep ocean, ecosystems, and health threats, and aimed at early detection. The arctic and harnessing data revolution are also included in the ten focus areas for NSF: https://www.nsf.gov/news/special_reports/big_ideas/.
- Fostering real-time assessment of these data.
- New interdisciplinary modeling and studies of convergent systems related to social, societal, health, ecological, agricultural, and economic impacts, including regional impacts.

- Resilience and adaptation for non-linear impacts, including for food and water supplies, for example.
- Improved research focusing on these tipping points, including understanding past examples.

Additional Ideas and Activities

The AGU community provided a wide range of additional ideas and input--more than 100 in total. These are grouped under four broad headings in the attached appendices:

1. Solutions already in place that can be scaled
2. New or unexplored ideas or focus area or research development
3. Area where previously disparate or uncoordinated efforts could be integrated
4. Some references provided by participants to relevant studies or further thinking

Input into each of these solutions is organized in these categories:

- Communication
- Convergent or Transdisciplinary Research
- Earth and Space Science Research (already within GEO and not convergent)
- Education and Training
- Environmental Justice and Equity
- Partnership or Community Priorities
- Partnerships
- Policy
- Science Societies

Some of these overlap with, and indeed helped generate the six major recommendations above. Some are more fully developed; others are short ideas. Others extend beyond NSF, especially related to the need for a broader culture change to reward and recognize CCS work. These are captured elsewhere.

Relevant References and Related Works

Participants were asked to recommend references and other works related to CCS and this guidance document. A list is attached. These complement some of the references and links provided in the text. They are collected and organized by general topic, although many apply broadly. These are meant to be illustrative and were not a full literature search or survey of recent guidance, e.g., from the National Academies.

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The list of participants is also attached, identifying those who attended each workshop and who self-identified as a student or early career participant.

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Appendix to: Report to NSF on AGU community recommendations and ideas regarding implementing Climate Change Solutions

This appendix includes the following:

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1. A solution already in place that can be scaled

Contents:

[Communication](#)

[Convergent or Transdisciplinary Research](#)

[Earth and Space Science Research \(already within GEO and not convergent\)](#)

[Education and Training](#)

[Environmental Justice and Equity](#)

[Partnership or Community Priorities](#)

[Partnerships](#)

[Policy](#)

[Science Societies](#)

Communication

1. Communications around the message that mitigation of climate change will now require both decarbonization (stopping emissions) and carbon removal (removing legacy emissions from the atmosphere, ocean, and biosphere). This messaging should specifically counter the narrative that carbon removal is a moral hazard for decarbonization. Work with social scientists to identify the right language and framing for maximum impact.
2. I have a lot of ideas, but the one that I have been thinking about the most relate to large centers focused on bridging research, practice, and training around climate change communication. There are centers like this at George Mason Univ (Center for Climate Change Communication) or the Climate Advocacy Lab -- but these are only able to focus on national efforts. If this could be scaled, it would make more social science and communications expertise accessible to groups working on climate change adaptation and solutions. I also think there is great work happening around participatory science and technology assessments that could be scaled up. I chose communication, but I think this also related to social science and several other topics.
3. The communication to various stakeholders and the public can be strengthened by providing high-quality and assessed climate information, data and services according to the approach of the IPCC Task Group on Data Support for Climate Change Assessments (TG-Data; <http://www.ipcc.ch/data>) and IPCC Data Distribution Centre (DDC).

The amount of available climate information and data is rapidly increasing. Information and data are linked and widely disseminated. Data is also copied into dark archives and disseminated by a number of portals that provide additional options for data analysis. It is often not possible to judge their quality.

The IPCC TG-Data and the IPCC DDC provide guidance for various stakeholders to obtain high-quality, assessed/reviewed information and data preserved in trustworthy repositories with a CoreTrustSeal certification/a World Data System Regular Membership. These assessed climate research data compliment the statistical data on the status of the Sustainable Development Goal (SDG) 13 provided by the UN SDG indicators (<https://unstats.un.org/sdgs/indicators/database/>) with future projections for support of political decisions. Transparent policies and processes for the assessment and the collaboration among DDC Partners and between DDC and external partners are of crucial importance for building trust. A professional communications officer in the Technical Support Unit (TSU) ensures the same high quality in the communication with various interest groups and the public.

With a Common Business model for sustainable operation of core parts – repositories, services, TSU – this approach can be scaled through new partnerships and enhanced high-quality/certified services in order to serve a wide range of stakeholders.

4. Building on existing approaches to science communication (such as from the National Academies, Rita Allen Foundation, and Alan Alda Center), design and implement programs to incentivize and train climate scientists to communicate their work to the public, advocates, and policymakers. Evaluate the programs to determine key factors for successful communications on climate. Relatedly, examine whether and in what ways climate scientists have a responsibility themselves to take on roles as advocates and activists.
5. Learning from and working with communities, scientific partnerships. For example, programs in place include AGU Thriving Earth Exchange, which can partner communities with scientists to address a current issue within the community. Others include collaborations with scientific organizations and policy-related organizations. By combining efforts, these organizations reach a larger audience. This is a solution already in place, and if more scientific organizations, and even universities, took on local community challenges pertaining to climate and environmental justice, this would be scaled up largely and have a positive impact for the community, the students working on the project, and the scientists leading the research.
6. cooperative extensions as a vehicle for communication and implementation of scientific innovations for communities across the country
7. Knowledge of the impact of short-lived climate pollutants (SLCPs) like methane, black carbon, and HFCs, has not spread very far, especially with the general public. Reducing SLCPs in the near-term is critical for achieving our climate goals - SLCPs are much more potent greenhouse gases than CO₂ but have shorter lifetimes in the atmosphere, so cutting SLCPs has immediate impact. Coordinated communications, outreach, campaigns, policies for local governments to cut SLCPs - all of these are needed.

8. Communication of climate change, down to individual activities. A system that can in real time inform what is the carbon footprint of specific activities.
9. Utilizing existing federal Public Service Announcement platforms: NSF in partnership with the AGU, AAAS and the directly NAS (or the proposed cabinet level climate office) create a new set of science based public service/social media events/products on the why, how, and public benefits of specific climate mitigation and adaptation actions (such as clean electrification) that are just and equitable. This could be akin to the authority the Surgeon General had in messaging about smoking, but via a new use of social media outlets.

Convergent or Transdisciplinary Research

1. The Trans-African Hydro-Meteorological Observatory (TAHMO.org)
2. Managing nutrients and hydrology to limit hazardous (toxic) algal blooms in freshwater ecosystems that are increasing in frequency and intensity due to warmer summers, threatening water supplies and human health.
3. Increasing soil carbon in working lands (cropland, rangeland, forests) using soil amendments and soil management practices such as silicate minerals for enhanced weathering (inorganic carbon sequestration), biochar, compost, cover cropping, reforestation/agroforestry, silvopasture, and holistic grazing management
4. The form of the 2020 NSF CIVIC RFP strikes me as an excellent model for solutions oriented research: a proposal for exploratory projects (4 months, low total \$ number) pursued in partnership with decision makers, followed by an opportunity to apply for a smaller number of larger implementation grants. This timeline is appropriate for true transdisciplinary engagement and could be applied in many other areas. The problem with CIVIC, as I've experienced it, is that in standard NSF fashion, it has taken a long time to get an answer. Proposals were due last summer and we still haven't heard about funding for the 4 month exploratory projects. That's long enough to lose the interest of government and NGO partners, so something should be done to accelerate the review process for those small first round grants.
5. NSF GOLD program. Promotes developing new leadership, research avenues and reward structures in geoscience.

Earth and Space Science Research (already within GEO and not convergent)

1. There are not enough funding opportunities for instrumentation. There's money to develop new tools, but little for expensive, out-of-the box instruments that we use every day. Many exciting instruments in my field were developed in the U.S., but are sold mostly to non-U.S. researchers. We need an investment in science infrastructure and affiliated staff.
2. Aquifer storage recovery (ASR) for irrigation purposes
3. No common approaches and conclusions in snow climate research, climate and land surface modeling, remote sensing, data availability, products validation
4. Participatory GIS
5. Add more Critical Zone Observatories (CZO). There are currently nine.
6. Scaling land surface processes with past time using climate proxies and paleo-climate models

Education and Training

1. NSF could support NRT- or NRT-style training program grants in convergent/transdisciplinary climate research. As NRTs, unlike IGERTs, cannot be renewed, and because five years is relatively short to achieve lasting institutional change, NSF should also consider some form of extended supplemental funding to existing programs that align with these objectives.
2. Building off the model of the former NSF GK-12 graduate fellowship program, NSF could provide graduate fellowships to support trainees who work with boundary organizations to provide climate services to communities, particularly low-income communities or those with substantial minority populations.
3. In alignment with President Biden's vision for the creation of a Civilian Climate Corps, NSF could support REU Sites that engage students in community-engaged convergent climate research that solves actually climate mitigation or adaptation challenges facing the communities.
4. Support and elevate the learning community and resources available through the Climate and Energy Awareness Network cleanet.org . Funded through NOAA, NSF, NASA and DOE. I used to be a lead on this project but am no longer in that role.
5. Involvement of youth - Youth Climate Summits
6. Carbon Reduction Challenge for college students (taught by Dr Kim Cobb & Beril Toktay @ GA Tech <https://www.carbonreductionchallenge.org/>, and adapted by myself at

University at Buffalo). This course or competition (can be run in different formats) partners students with organizations/businesses, the student teams then count the organization's carbon and work with the org to develop an immediately actionable plan to reduce that footprint. Previous competitions/courses have reduced CO₂ emissions by millions of pounds annually, and have the potential to accomplish exponentially more savings. In addition, partnering with small and Women and Minority Owned Businesses will help them remain competitive and save money moving forward. This curriculum/competition can be readily expanded to other colleges/universities across the nation and world.

7. Climate change educational training

8. We work with a grassroots organization of self-organized young folks that are passionate about STEM and climate change in the Meadowlands of New Jersey. These groups are mainly self-organized but are also linked to STEM-oriented Magnet Schools which attracts the most talented high school students in Northern New Jersey. They and other similar groups provide an excellent core of potential citizen scientists where new talent and skills can be developed around hands-on sea level rise and carbon sequestration measurements.

The idea is to create a way for these young folks to become involved in measurements related to climate change in their local area. They would join and expand existing stations that measure sediment marsh elevation change and levels of carbon sequestration. The currently established programs in these areas could be scaled up to provide students with real hands-on experience in local climate change science. These stations are sampled every year and therefore provide a repeating activity for the senior class.

Sediment Elevation tables. Students will become familiar with the sediment elevation table (SET) technique to measure wetland subsidence and accretion. They would join and expand measurements from an already well-established network of SET's

Carbon sequestration (indirect method). More tech-oriented students can participate in measuring carbon sequestration using the eddy covariance method. This activity involves digital sensors and requires data analysis using advanced software and digital tools. Currently, there is a small network of these towers in the Meadowlands of New Jersey that could be expanded in place and to other estuaries.

Carbon sequestration (direct method). Students would use a Russian peat core to extract cores and determine the amount of carbon buried in the sediments. This direct method serves as verification to the Eddy Covariance Method. This approach provides students with the opportunity to gain fieldwork experience and develop laboratory analysis skills.

The proposed above can be scaled up to other estuaries in New Jersey and nationally. These talent and skill developing can be streamlined and fall under a single banner, something like: "Coastal estuary Climate Change observation initiative".

9. Graduate student collaborations on community projects

10. Heat early warning systems, generally, and specifically in countries like India
11. UCLA Center for Diverse Leadership in Science - Aradhna Tripathi's work. Highly evidence based; building mentor networks, community of practice, some financial support for students, inclusive and very diverse community to train students in "Green STEM" fields. Includes community-driven research, connections with Indigenous communities. Prepared to scale to other MSIs (and there is an NSF S-STEM proposal under review currently to do so), with structure, mentor training, peer networks between institutions.

Environmental Justice and Equity

1. Cross-matching coastal flooding models with US Census data
2. Reliable, robust broadband internet access for all, especially rural and other underserved communities
3. NSF could fund the establishment of "science shops", which are centers for research that are driven by community concerns. Science shops would be established collaboratively between scientists and community groups. Science shops provide infrastructure, including time and equipment, for research questions brought by communities. Communities may otherwise find it challenging to get access to specialized equipment or knowledge or expertise to run specialized equipment or answer scientific questions. This solution aims to provide immediate and reliable access to scientific resources for underserved communities. Researchers, including graduate students, could be funded to work on these problems alongside community groups through the science shop. The small-scale research that is performed at science shops could form the basis for larger collaborative proposals with community groups in the future. There are existing non-profit science shops, which are more widespread in Europe than the US, and other similar participatory research programs.
4. The HBCU Climate Change Consortium has led and participated in a number of conferences and initiatives to raise awareness of the effects of climate and environment change on marginalized communities. Their leadership efforts could be better supported and scaled,
<https://www.dscej.org/our-work/hbcu-climate-change-consortium>
5. Relational approaches to community partnering/Coproduction of research & education for student & community outcomes. We can make science (research & education) more aligned with decision making (see Schalet et al., 2020) to advance equity & justice. There is also an opportunity to leverage civic infrastructure at universities or educator web infrastructure & community building strategies that have propagated educator communities & effective pedagogical practices (e.g. NSF InTeGrate).

https://www.umass.edu/pep/sites/default/files/schalet_tropp_troy_2020_-_making_research_usable_-_relational_model_of_public_engagement.pdf

6. Community solar (ala WeSolar)

Partnership or Community Priorities

1. Restoring & grazing grasslands in dry regions, eg western slope Colorado, Arizona
2. Execution of a project designed by the University of South Alabama for the Dulac Band of Biloxi-Chitimacha-Choctaw Tribe in Louisiana to build floating houses; walkways; and food gardens. The tribe it is the first community in the US that is losing its land due to climate change. They wish to adapt to the change. It is a tribal priority.
3. Solar installations coordinated with restoration on agricultural lands where it is too dry to keep farming.
4. Identification of emissions hot-spots (e.g. methane) from animal waste/landfills/gas leaks (see e.g. Marklein et al. 2021 ESSD, Rafiq et al. 2020, both of which deal with identifying point-source methane emissions in California's central Valley). Partnerships with Agricultural science and (e.g. dairy) Farming communities.
5. The Thriving Earth Exchange of the American Geophysical Union
6. Mitigation through a marked reduction of tropical deforestation
7. Actionable Community-Oriented Research eNgageMENT (ACORN):
<https://pcc.uw.edu/research/acorn-program/>
Graduate students in the University of Washington Program on Climate Change cofounded ACORN in early 2020 to connect UW graduate students with community leaders in project-based collaboration addressing community-driven priorities related to climate and energy. In addition to supporting community priorities with solution-focused science, ACORN projects train the next generation of scientists to engage beyond academia. ACORN projects are currently volunteer-based, but we seek funding for administrative support and equitable compensation of graduate students and underserved communities who would otherwise be unable to participate in an ACORN project. Modeled after the AGU Thriving Earth Exchange approach to community science, programs like ACORN could be expanded to other universities, and we've already begun to collaborate with students at Columbia interested in starting a similar program. NSF funding for university-based community science programs like ACORN would help catalyze solution-focused science with direct community impacts and training benefits for the next generation of scientists.
8. Sea-level rise by 2100 under strong warming is projected to be ~1 m, with uncertainties of ~1/3 m on the low side and perhaps 3 m or more on the high side. Fracture-mechanics processes could lead to ice-shelf loss and calving-cliff retreat that greatly increase sea-level rise from Antarctic basins. This is arguably the single biggest climate-related "tipping point" in physical systems on Earth (biological and human systems clearly have hugely important tipping points, too). The research on this is

largely funded out of NSF "core" budgets, with no additional initiative funding. None of the ice-flow models that informed the most recent IPCC projections to 2100 includes representations of these processes. (One model to date does so, but was not included in the projections.) There is great room for additional funding. There may be real opportunities to entrain additional expertise from communities with relevant expertise, such as those who study landslides, earthquakes, rock mechanics, etc.

9. At the Nicholas Institute (Duke University), we kicked off an Energy Insecurity project earlier this year that aims to more deeply understand the the impacts of energy insecurity in the Southeast and the tradeoffs our households face every day. We have established an Advisory Board of leading environmental justice and low-income advocates, including some from state agencies and utilities, to help guide our project and map a set of solutions that we can accomplish together. This is only a one year project, but we feel it could be expanded into a much larger, longer project as we work to educate others and implement the solutions we collectively come up with.
10. Linking Climate modeling to climate risks for equitable solutions using adaptation, mitigation, and localized low-risk climate interventions
11. Recycle, reuse, reduce
12. Many land grant university have university extensions that connects the entire state. These extensions are a valuable asset for public universities to understand the urgent need of local community and work closely with the community through the established and trusted partnership to disseminate information and implement adaptation and mitigation strategies to respond to the changing climate. This partnership model should be catalyzed and expanded so climate solution-oriented research can be done directly in conjunction with the community and integrated into actions much more efficiently.
13. Heat wave preparedness planning at the local level (blending weather forecasting, downscaling, EJ analyses, public health, communications)
14. Thriving Earth's community science partnerships between communities (of all types), scientists and project managers. These projects always start with community priorities first and then find appropriate scientists to work collaboratively with community leaders to develop and implement relevant tools and solutions.
15. Actionable Community-Oriented Research eNgagement (ACORN):
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approach to community science, programs like ACORN could be expanded to other universities, and we've already begun to collaborate with students at Columbia interested in starting a similar program. NSF funding for university-based community science programs like ACORN would help catalyze solution-focused science with direct community impacts and training benefits for the next generation of scientists.

16. Massive deployment of RAPID grants for carbon removal strategies
 - a. Faster/Shorter funding cycles for proof of concepts with follow-on successful ones
 - b. In collaboration from the inception with communities who it will impact

Example focus areas:

- Ocean CDR (unintended consequences, permanence)
 - Validation of soils as a natural climate solution (in situ measurements, remote sensing)
 - Life cycle analysis for CDR
 - Direct air capture
 - Carbon dioxide utilization (e.g. in concrete)
17. Fund actionable research for institutions and think tanks on urban climate solutions applied in the cities where the researchers are located. This will enable place based research with actionable insights and a meaningful local impact. Researchers need to know the specific details of each problem they are trying to solve and interact with either businesses, policymakers, or any relevant stakeholders for quantifiable actionable outcomes. Expanding place based and actionable research for urban solutions will be key for sustainable cities.
 18. Restoring & grazing grasslands in dry regions, eg western slope Colorado, Arizona

Partnerships

1. The National Ocean Partnership Program (NOPP) promotes partnerships between academic institutions, government and industry to meet major challenges. This is a good funding opportunity model especially for major initiatives over time scales of 5-10 years.
2. A partnership between scientific and infrastructure partners together with a program office is set up for WCRP WGCM-CMIP (<https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6>).

Data and infrastructure are key in climate sciences. A collaboration of a research panel (CMIP Panel), an infrastructure panel (WGCM Infrastructure Panel) and a program office (CMIP-IPO) for support and coordination grants that data and infrastructure are fit for the planned research and complies with best practices in data management and data services.

This approach can be applied for the regional climate science and impact research area.

3. Connecting sea rise/flood, fire risk, and extreme climate event data to specific real estate locations, portfolios and buildings, and then developing mitigation strategies to address them. There are companies gathering data to advise large portfolio owners to help them assess their property risks, value, and to help them either reposition, dispose of or select locations for real estate investment. As buildings are a huge portion of the climate problem, property owners, investors and banking institutions need to understand and be prepared for major changes, particularly, but not exclusively to coastline real estate. There are a number of competing software programs out there that do not necessarily align or use the same underlying criteria. Having national standards for this would be useful and put everyone on the same playing field.

<https://www.cnbc.com/2019/08/08/these-start-ups-lead-the-race-to-predict-climate-risk-for-real-estate.html>

<https://www.esgtoday.com/moodys-adds-climate-data-into-ratings-for-real-estate-linked-securities-and-debt/>

ULI (Urban Land Institute) also has a number of studies on how climate risk is affecting real estate value.

<https://www.mckinsey.com/business-functions/sustainability/our-insights/reckoning-with-the-overlooked-business-risks-of-climate-change#>

4. As described in the below answers, lightning is just coming into the fold as an "essential climate variable" designated by the WMO. We are just learning how lightning is both an indicator of climate change, and an accelerant (like triggering forest fires).

Investing in accurate ways to locate and characterize global lightning in the long term would be useful. There are existing global lightning geolocation networks that could be improved and scaled up to serve the climate change needs (they were initially built for other purposes).

Partnerships with certain universities and commercial companies will be helpful.

5. Co-development of solutions with strategic partnerships.
6. ICNet Global - a global collaboration between Transportation engineers/designers/planners and climate scientists. PI Jennifer Jacobs at UNH
7. The NSF Directorate for Geosciences should capitalize on new, and new types, of industry-university partnerships to catalyze transformative, cutting-edge, use-inspired, purpose-driven research in atmospheric, ocean, coastal, geospace, polar and other relevant fields pertaining to climate change. Relevant stakeholders (e.g., private sector, utilities, state and local governments, federal agencies and national labs, regulators, nonprofits) should engage directly with GEO to inform the development of relevant mechanisms to catalyze translational research from the GEO portfolio. These efforts

should enable critical, shared needs of commercial and governmental entities that require better or new types of fundamental research; translate fundamental research results to society and the marketplace via innovation and technology development; and help develop a diverse, highly skilled, science and engineering workforce that understands how to work with industry or become entrepreneurs. Previous models at NSF include but are not limited to Engineering Research Centers, iCorps, IUCRCs, SBIR, STTR, and ATE. Integration of community colleges, certificate programs, and other industry-driven educational pipelines should be encouraged.

8. Surface albedo modification of ice and snow, work is currently estimated to be at TRL-3 for a localized method using HGMs (hollow glass microspheres). Work is needed to scale, including climate modeling, material performance and cost evaluations, and evaluations of safety and efficacy and possible deployment methods.
9. California's Strategic Growth Council--it coordinates and works collaboratively with public agencies, communities, and stakeholders to achieve sustainability, equity, economic prosperity, and quality of life
10. Partner with NOAA Regional Integrated Sciences and Assessments (RISA) program
 - a. Identify successful models of engagement and capacity building prototyped via the NOAA RISA program and scale them. Example: Spokane Community Adaptation Project (<https://pnwcirc.org/spokane-community-adaptation-project>) in which local community members paired with RISA team members to support community-driven, science-based climate adaptation planning
 - b. Gather user research about broad climate data usage to develop best practices of information communication

Policy

1. Legislation on climate policies that is actionable and scientifically sound. Better coordination among science agencies is needed as well as regional solutions. A regional solution example: for western U.S. states, policies on mitigating and adapting to wildfire and limited water resources is needed. This can be done through science agencies such as NSF, AGU but also non-traditional groups like ranchers, farmers, forest managers, and local communities. An example of a broad action would be carbon dioxide removal strategies. This is relevant country (world) wide, can involve science, engineering, and *critically* industry groups to apply technologies to the problem. If they are not expensive and provide economic benefits, they will be done.
2. I recall giving community "lectures" in the early 1970's regarding wind, solar, and nuclear energy sources as goals to supplement (not replace) conventional energy/power sources. Stop using the term "Green;" it has become politicized. Stop referencing ideas about "transitioning" from an oil and gas economy/power source; it too has become politicized and we will never in reality not have some use for oil and gas.
3. science and technology policy fellowships at the federal and state level

4. Restoration of coastal ecosystems ("blue carbon") is a powerful, natural carbon dioxide removal strategy, that needs to be supported and facilitated by state and federal government policy. Large projects, which may have many administrative and financial hurdles, need to be advanced with the help of federal mechanisms. This strategy would be greatly assisted by having a national strategy that would allow cooperation among regions and sharing of information across sectors.

Science Societies

1. FAIR data principles are starting to be applied in climate and other natural sciences, the social sciences and the humanities: they need to be able to scale with the ever increasing and complexity volumes of relevant data and further, the science societies need to endorse the standards (in particular vocabularies) that are critical to Interoperability of data required and more importantly, reuse of any existing data in the context of climate solutions
2. Prediction of infectious diseases using climate, hydrological and sociological processes

2. A new or unexplored idea, focus area, or research development on any of the above topics (or other relevant topics):

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Communication

1. Real time climate change event attribution statements
2. On the subjects of communication, climate science information-sharing, and measuring the public understanding of climate change and viable solutions, I think more evaluation and assessment research is needed to better understand what teaching, learning, and communication strategies are most effective. The University of California Museum of Paleontology recently launched a new Understanding Global Change web resource that encourages the use of storyboards and graphic models to demonstrate connections between the drivers of change and measurable impacts, <https://ugc.berkeley.edu/>. Assessment of the UGC resources is in the early stages but projects like this suggest conceptual gaps exist that may prevent next-gen scientists from fully understanding the complexities of climate science and creative solutions.
3. Bidirectional communication, where citizens not only receive notifications, but they can contribute data. For example, they could report unusual temperature, erosion, invasive species (plants and animals) that can inform climate change science. Therefore citizens become not only receiver of communications, but they actively participate in their collection and distribution.

Convergent or Transdisciplinary Research

1. Rewarding transdisciplinarity
2. The role of the ocean in potentially providing gigaton-scale removal of carbon dioxide pollution from the atmosphere necessary to stabilize, and ultimately reverse, global warming
3. Climate Change and AI
4. "Partnerships between local, regional and global levels as well as between different research areas and stakeholders need to be strengthened.

The most important and most efficient level for collaboration between physical climate researchers, impact researchers and policy advisors is the national to sub-national level, where impacts are observed and decisions are made. A network or platform is needed to bring these different stakeholders together. The inclusion of indigenous knowledge (CARE principles) and a professional communication officer is important. The embedding of national networks in an international network is necessary in order to support the establishment of partnerships from local to global level as well as interdisciplinary and transdisciplinary.

The exchange of information and data between experts via these networks can create incentives for research directions and guide decisions. In addition to a network of experts, sustainable and high quality information, data and customized data services for the various communities are essential.

5. Incorporating climate risk factors (science) into building science (engineering)

The design, construction and operation of today's built environment are largely based on the science and experiences of the past. Yet, the future requirements of buildings and other infrastructure across their life cycle are likely to be vastly different. Natural hazard events are changing in frequency, intensity and impact. This new paradigm requires that the planning, design, construction and operations workforce has the tools to address these new types of challenges. There is a strong need that addresses these evolving risks through the engagement of necessary stakeholders from the climate science and building science communities along with representatives from insurance, finance, government and academia. This is where science marries with engineering. And we have a great model that we may mimic under the National Earthquake Hazard Reduction Program (NEHRP), where the U.S. Geological Survey (in large, the earthquake science community) and the National Institute of Building Sciences Building Seismic Safety Council (in large, the engineering community) worked together to produce the US Seismic Design Value Maps to be used by the building industry.

6. Standardize construction/design components to the extent possible and energy transmission and storage mechanisms to avoid incompatibility between regions of the country (for wind, solar, and nuclear).

7. Improved collaborations between engineers/geoscientists focused on climate solutions and humanities scholars/social scientists who can address the economic/social/cultural implications and barriers to implementation of climate solutions
8. Genuine transdisciplinary research in which data and research outputs from the natural, social and health sciences can be seamlessly integrated and harmonized across their traditional boundaries, without impacting on the integrity of deeper disciplinary research
9. There have been sporadic indications that lightning, particularly in the arctic, will increase substantially as climate change progresses. This matters for two reasons: (1) Counting lightning accurately can potentially provide a new perspective on where climate change is advancing. (2) Lightning may be an accelerator for some climate change processes, by increasing forest fires. For example, in the arctic, more forest fires triggered by lightning weakens the permafrost.
10. Quantified economic assessments of adaptation responses for specific infrastructure assets. This will need to be collaborative to identify changing risks, required design strategies, and the financial implications (including/especially indirect costs such as ongoing health conditions or lost work hours).
11. Recent ground-breaking advances in AI have been enabled by increased computing power, algorithmic improvements in machine-learning, and the availability of large data sets. Synergies between research frontiers in AI and the Geosciences have the potential to stimulate further transformative progress in both fields. Develop a program and fund research to develop artificial intelligence systems to integrate with climate science research and solutions.
12. Preservation/restoration of reflective Arctic ice to slow climate change impacts, giving a few more years to complete the urgently needed transitions to longer-term sustainability, mitigation and adaptation measures. There is still much to do in this area in terms of climate modeling to determine proposed limited strategic areas of most positive potential benefit; performance and safety testing, fate studies, deployment methods.
13. Learn from remote communities the ethics and practices to sustainably and responsibly recycle, reuse and reduce energy and material consumption
14. In the recent address by President Biden to the joint session of the Congress, two key words have emerged - jobs & economy - when it comes to the climate crisis. AGU's statement on the climate crisis also cited the economic benefit of addressing climate change. But the collaboration between Earth and space scientists and economists are still far from mainstream. Two communities operate in different modes of research (how the research is conducted). But it is vital to foster close collaboration between these two groups to demonstrate both the economic side and the climate side of the story. This collaboration should be communicated effectively to the public and stakeholders which will ultimately lead to legislative actions which will ensure a robust response to the climate crisis.

15. Research on determinants of attitude and behavior formation relative to climate change (the ways we travel, the food we eat, our consumer choices, our buildings). As a model see Cardiff University's Centre for Climate Change and Social Transformations (CAST).
16. We need much expanded research on the economic impacts of climate change on health--both the costs of climate-related events such as wildfires and heat waves, and the potential savings of solutions such as decarbonizing our electrical generation. These economic analyses are highly effective in shaping policy. The research needs to combine earth sciences, health sciences, and economics.
17. Produce quantitative models of the social, behavioral, and mental health impacts of climate change (at local, national, and global levels) to enable projections of future trends and needs under various scenarios and policy choices.
18. Project future climate-related migrations and needs of displaced populations to guide policymaking and resource allocations by governments and the private sector.
19. Encourage researchers who develop behavior change interventions to focus on behaviors that will have the greatest impacts on climate and people's adaptation to it. Interventions should be scalable to large and diverse populations. Some examples of research topics:
 - a. Design technology and behavioral practices that enable business and academic activities (individual work, teamwork, and conferences) to be conducted virtually in ways that are effective and satisfying for all participants, thereby reducing needs for commuting and long-distance travel.
 - b. Economic and behavioral aspects of shifting to diets containing fewer meat and dairy products.
 - c. Identify key elements of successful community resiliency projects and organizations, including those that address psychosocial resiliency (rather than infrastructure only).
20. Examine the knowledge and attitudes of young people about climate change and how considerations of climate are affecting their current behavior and life plans.
21. Conduct research on climate activism – who participates and why, what impacts does it have, what are its successes and limitations, and what role it can play in future responses to climate change.
22. Metallurgy, especially as it related to processing and recycling critical minerals for energy storage.
23. Virtually all natural Earth surface systems, as well as numerous components of the built environment, are strongly affected by the growth of fractures in rock. As rocks at or near Earth's surface weather and respond to climate and tectonic forces, the associated fracture growth changes their strength, porosity and permeability. In turn,

these changes have significant societal and natural-process implications. The stability of natural and artificial slopes, excavations, deep boreholes used for energy production, and the evolution and architecture of the Critical Zone (the area defined by the National Science Foundation [NSF] as comprising from the top of the tree canopy to the bottom of weathered bedrock) are all intimately linked to these changes.

For example, crack growth likely governs rates and modes for processes ranging from CO₂ cycling (e.g. Raymo and Ruddiman, 1992), to regolith production (the conversion of bedrock to sediment; Brantley et al., 2017) to hillslope sediment supply (DiBiase et al., 2018) and bedrock channel incision (Shobe et al., 2017). Crack growth also impacts the management of aging infrastructure, the conservation of our archaeological heritage (Hall, 2011), and our understanding and assessment of risk related to hazards like landslides and rockfalls (Stock et al., 2012).

A wealth of engineering literature supports the idea that rates of crack growth in the natural and built environment are directly tied to environment (climate) and are typically non-linear, manifest as slow, progressive (subcritical) deformations that can accelerate without obvious warning towards rapid and hazardous macroscale critical rock failure (hereafter Progressive Rock Failure (PRF)). However, the factors (e.g. climate) that drive or limit fracture growth itself (typically studied in the context of ‘mechanical weathering’) remain poorly characterized (e.g. Sklar et al., 2017).

Virtually all research focusing on mechanical weathering processes or on geologic hazards related to fracture are, in fact, addressing the stress loading mechanisms that induce rock breakdown, such as thermal cycling, freezing, or precipitation events. Geomorphologists have therefore long assumed that mechanical weathering operates solely as a stress-related process whereby the ‘strength’ of the rock must be exceeded for cracks to grow.

Considerably less attention has been focused on the fundamental cracking processes, the biogeochemical and climatic processes that can accelerate them, and how they influence Earth surface processes.

In contrast, engineers have long recognized that the molecular bond-breaking that drives PRF is strongly linked to crack-tip environment, and can proceed at stresses much lower than a rock’s critical strength (e.g. Atkinson, 1984). Despite the obvious relevance of these insights to weathering, geomorphology, hazards (like rockfall and landslides), and climate-mitigation (through silicate weathering), applications have been limited and so potentially highly complementary approaches (Engineering vs. Geomorphology) to PRF remain disparate, constrained by traditional disciplinary divides.

Even in geoscience and geotechnical fields where PRF has been more widely incorporated into the discipline’s lexicon and approach (in the context of, for example, fault creep or tunneling), improving our understanding of environment (climate’s) role on subcritical cracking, and the mechanisms, rates, scaling and consequences of its effects, has posed extreme challenges. In particular, progressive weakening of rocks resulting from microscale crack growth through time is not easily perceptible. As such, constraining the long-term controls on PRF has proved difficult. However, new technological advances are enabling clearer understanding of the properties and

growth of fractures. Similarly, advancing modelling techniques are demonstrating the potential to link across scales, from crack tips to rock microstructure and ultimately to a scale that can be applied to Earth surface processes and change. However, these engineering studies of underlying crack-growth processes are all limited in their duration. They are focused on timescales of microseconds to a year at most, and generally are driven by relatively short-term engineering needs and applications.

Many fundamental questions of temporal and spatial scaling remain. However, geomorphologists have the tools and study designs to link the small spatial and temporal scales to hillslope and landscape scale processes over significantly longer timescales. Bringing the PRF Rock Physics, Surface Processes and Geoengineering communities together has the potential to open the door to a myriad of new frontiers, applications and validations of all geologic work linking climate change to rock fracture.

24. The effectiveness of heat early warning systems in different settings continues to be an open question. The issue of how best to scale these systems and implement them without losing effectiveness is another important question.
25. Research into mineral supply chains which are relevant for batteries, solar, direct air capture (DAC) feedstocks, and surface mineralization
26. Research on the sustainability and feedbacks associated with natural climate solutions (e.g. forest or soil carbon sequestration) and the role that large scale land management can play in mitigating risks.
27. Research on how different land management approaches affect soil carbon/nutrient dynamics across a broad suite of geographies, climates, and agricultural contexts (e.g. the same cover crop will have a different effect in Washington as compared to Colorado). * Deploying extensive in situ measurement campaigns to ground truth remote sensing estimates. High quality datasets would (1) support data-driven decisions around context-specific land management practices to support carbon sequestration (2) provide accountability for carbon markets (3) improves existing greenhouse gas inventory
28. Research into climate impacts on labor, especially on industries disproportionately served by low-income and BIPOC communities

Earth and Space Science Research (already within GEO and not convergent)

1. For regional adaptation, particularly for understudied topics/areas such as precipitation trends in the developing world, there should be more research and concerted effort to compare CMIP historical simulations to actual observed trends (up to century scale) to: 1) help understand where detectable anthropogenic trends are emerging and 2) where models may be unable to reproduce observed trends even accounting for natural variability, so that more work is needed for reliable projections.
2. Using EO/RS to assessing the environmental drivers virus and vector borne diseases and their impact on social, economic and ecological structures

3. Economical solutions to clogging problem in managed aquifer recharge (MAR) system.
4. Terrestrial Snow Cover represents a significant gap in scientific studies, especially fractional snow cover
5. Using multi-angle remote sensing observations for a better atmospheric correction, which leads to a better classification of solid, liquid and gases. These observations could give an unprecedented accuracy to estimate the carbon footprint of different activities.
6. Climate engineering/geoengineering
7. Localized nature-based climate interventions to intervene in and slow critical accelerating feedback loops (such as arctic ice melt) should be considered and funded in addition/ separately from the more often-considered global atmospheric interventions
8. Global climate and land surface interface model coupling
9. Geothermal - basic and translational research. Leverages continental scientific drilling, which is one of the areas recommended for expansion in the NAS Earth in Time report.

Education and Training

1. Community based climate observation linked to education in resource-limited settings
2. Much broader practical use of geo-spatial tools in science education and training so that students can understand global connections and the scales of climate change problems.
3. One of the critical training gaps that I have seen in graduate education is identifying the stakeholders in research questions and working with a wide range of stakeholders. Education on this topic would involve teaching scientific disciplines in their social and historical context from a critical perspective to highlight the main current stakeholders and to help students identify areas for growth in the social relevance of their discipline.

As one concrete proposal on this topic, I think it would be very impactful to expand existing science policy programs to focus on local politics. Climate adaptation will be carried out at the local level and will only be socially just if it is responsive to local needs. Scientists are often asked to or could volunteer to serve on local committees and boards and there is often a lack of resources available for crafting policies or carrying out assessment studies at the local. Training and support for climate scientists that focuses on socially just climate responses through local politics (such as county or city-level politics, on conservation district boards) could help to increase community engagement by scientists and help to reimagine scientific careers to support climate solutions. Scientists serving local government on a volunteer or elected basis would have to learn to work with people across different stakeholder groups and would be some of the first advisors to how to interpret and act on climate risk."

4. Develop a new "standing forest bioeconomy" for tropical rainforests, particularly through forest restoration in agroecological systems
5. Add personnel funding opportunities to equipment grants. It is becoming more and more difficult to pay expert staff to operate/maintain research equipment. Equipment grants could be combined with funding for staff and undergraduate/graduate students to develop technical expertise. Training students takes a lot of time and we need staff time to support this. I think there's an under-utilized opportunity for careers in STEM that are more technical.
6. Critical training gaps. For example, I am a first generation geoscientist and graduate student. I was lucky enough to be selected by different organizations to be part of science policy cohorts, where I was trained on the ins and outs of policy work and advocating for science legislation. I also learned science communication as part of this as well. Not everyone has access to these opportunities. If there could be some type of program or initiative to make these trainings more accessible, more geoscientists may feel they can join in these conversations and discuss climate; with more of us at the table, climate solutions would be developed from all backgrounds.
7. Using cooperative extensions to offer afterschool/study/training opportunities to youth in local communities to increase diversity and representation for careers in practical/solutions-oriented science, stimulating a future science workforce that represents diverse communities and focuses on practical science with goals towards implementation - a more science-oriented 4H that brings youth in closer contact with scientists, and reaches youth not just in rural communities
8. NSF STC style program focused on improving DEI in STEM
9. A focal point for STEM: New educational curricula about the processes and interconnections of earth systems with human activities — environmental science for K-12 that is more rigorous and science based than its current state. This could be stimulated by funding opportunities via a collaborative effort between NSF Geosciences and NSF Education. An outcome could be better linking of secondary education to academic pathways at the undergraduate level that prepare students intellectually as informed citizens, but also to feed the career pipeline for the likely growing demand for expertise in adaptation/mitigation/resiliency and sustainability oriented applications of science & engineering.
10. A research fellow program where new PhD's can do a year long post-doc with industries in this space. We were calling this Research Fellows - a workforce training program in the future.
11. Support research and graduate programs that encourage a wider range of behavioral and social scientists to address climate change. Currently only some subfields are significantly engaged in climate issues (e.g., social and environmental psychology, but not clinical or industrial-organization psychology).
12. Make explicit efforts to attract and retain a more diverse set of students and investigators for climate change research, especially those who come from

disadvantaged groups and communities that experience the greatest impacts of climate change.

13. For all levels of education (elementary through graduate school), develop curricula and teaching materials on the social, behavioral, and health dimensions of climate change. In addition to developing students' knowledge and critical thinking, address their attitudes and emotional responses to climate change and climate justice.
14. Promote informal science education about climate change through the media, museums, and community organizations (including preventing and responding to science denial and disinformation).

Environmental Justice and Equity

1. Supporting teaching & research at Minority Serving Institutions
2. The impact that the lack of broadband access on on health outcomes in minority communities, particularly COVID 19 death rates. Preliminary research in Georgia and South Carolina indicate that the lack of access to health education and information via broadband (internet) has significantly increased poor health outcomes in a number of areas, such as cancer, heart attacks, asthma, and particularly COVID 19 death rates. Additional studies are being done in Northern Louisiana in African-American communities, and in New Mexico in tribal communities. However, this needs to be a nationwide study to ensure that this area of healthcare support is fully understood
3. Establishing field stations with labs in conservative, rural communities and communities of color with the aim to develop community science to serve these communities.
4. How restoration of coastal ecosystems could reduce risk to minorities and at-risk populations
5. Potential for alternatives in food production and changing demand (e.g. there was a recent editorial by Ezra Klein in the NYTimes about initiatives to rapidly expand development of alternative proteins to reduce expanding demand for meat)
6. I would love to see funding for community-based climate resilience research, or at least significant elements. Current opportunities (e.g. SRN) include community-based research but it seems like more of a nice to have than as a primary design value. Many researchers want to do more community-based research but lack skills and understanding of authentic partnership.
7. I think a relatively under-explored idea or area where much more work needs to be done is around science communication and other engagement activities, such as co-production, and how to do this work in a way that gives more power and resources to groups that are trying to respond to climate change in their communities in culturally relevant ways. As a social scientist, I would love to see communities receive funding and to play a supporting role in achieving climate adaptation or mitigation goals by lending my expertise. I selected environmental justice and equity, but this also relates to

communication, social science, and crosses a lot of sectors depending on the situation. Now that I think about it, this shares a lot of commonalities with the AGU Thriving Earth Exchange model.

8. science policy fellowships for local/municipal governments to increase access to resources of science for decision making particularly for small and rural communities otherwise left without access to (or even, particularly skeptical of) science
9. Knowledge coproduction with community stakeholders, especially in tribal nations and with indigenous scientists
10. Supporting teaching & research at Minority Serving Institutions

Partnership or Community Priorities

1. Social science exploration and documentation of science ideologies that are counter to liberty and justice for all: how and why do these emerge? Do they exploit the belief in "scientific objectivity" to warp social structures towards caste, class, and other inequitable social structures?
2. Citizen scientist network to use microscope attachments to iPhones to report potentially hazardous algal blooms in an iNaturalist approach. Would need to manage responses and perception of risk.
3. The NSF could get on board with proposals for a Civilian Climate Corps, via a program that would engage Climate Corps participants as liaisons for science-informed climate action. As liaisons, the Climate Corps members could identify research needs, encourage local officials to propose to programs that partner communities with scientists, and take part in workshops devoted to specific climate action topics. In a sense this would build from TEx models, but with built-in champions in communities across the country. Ideally such an effort would be paired with funding RFPs for greater engagement (e.g., things like S&CC, CIVIC, etc.).
4. Training, mentoring, internships between strategic partners to ensure our future workforce has the necessary boundary discipline skills to enable communications between diverse sectors.
5. Participatory GIS for community engagement on climate changes
6. Linking climate modeling to flood, fire and insurance risks to help achieve equity in resilience and policy decisions on adaptation, mitigation, and localized restoration/regeneration solutions
7. Develop university students, researchers and faculty expertise in addressing for and non-profit business questions about carbon sequestration, offsets, etc.

Partnerships

1. A mechanism to provide seed funding for early career researchers to develop new stakeholder/community partnerships. This is a time consuming endeavor and needs to be done well in order to make meaningful impact, but there is no mechanism to fund this *prior* to receiving a funded proposal
2. "Spencer Glendon of the Woodwell Climate Research Center is working on these issues and has helped develop a way to include climate risk into real estate pro-formas, which is the financial analysis instrument used by developers to evaluate real estate capital improvements, purchases and new development. He has partnered with McKenzie on a number of reports in this arena. It may be this could be connected to specific geography data as noted above to create something more comprehensive and ""standardized."

<https://www.woodwellclimate.org/staff/spencer-glendon/>

<https://www.mckinsey.com/business-functions/sustainability/our-insights/reckoning-with-the-overlooked-business-risks-of-climate-change#>"

3. AGU carbon cycle scientists and policy experts could be helpful to corporate America and state governments as advisors and teachers regarding carbon science and potential strategies for decarbonizing their operations, or at the very least, mitigating them. Sustainability officials in companies often cannot get access to current research that would provide the basis for major changes in corporate behavior regarding climate change. This is an opportunity to form new partnerships and engage on information sharing and specific projects with the corporate as well as state government sector. This opportunity for engagement would likely spur many new research ideas for AGU members who become involved. From the offset, such partnerships could strive to engage with a highly diverse corporate and state sector, ensuring values of equity and inclusion.
4. Establishment of Community Equity Councils to address health equity & climate challenges in post-COVID recovery

Policy

1. The coproduction of knowledge to advance community outcomes should be researched in more detail. What infrastructure supports coproducing research & education in the sustained ways needed to make systemic change? How might we design research that embeds disciplinary knowledge needed to characterize/forecast/evaluate and the education & education research needed to build capacity & advance two way learning so that mitigation/adaptation strategies align with frontline priorities/policy interests.

Science Societies

1. Involve youth in research with communities and scientists - it will help generate interest and passion for STEM careers. Youth can help connect researchers to local communities and make their research actionable.
2. AGU and other big societies should actively discourage travel by scientists to meetings by continuing with 100% virtual conferences with enhanced virtual networking opportunities. We did this for the last 15 months and we are still doing great science. It would set a great example and have large carbon savings going forward! Encourage scientists to take a pledge to cut science-related air travel.
3. Looking at human health and water quality affected by climate change-driven water stresses in disadvantaged communities. Use of systems approaches to interface science and engineering with social and behavioral sciences.

3. An arena where previously disparate or currently uncoordinated efforts could be integrated to multiply impact and reach:

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Communication

1. Information maps by zip code - where are communities getting their "facts"?
2. Right now NSF spends a lot of money funding the broader impacts efforts that are included in natural science projects. My sense is that these rarely rely on the best available social scientific evidence and they often lack clear goals and objectives. To coordinate these efforts, ensure that they are based on how people actually think, feel, and behave -- that would be paradigm shifting in the science-society interface.
3. Research clearly shows that until public opinion is swayed to understand and appreciate the climate crisis, meaningful adaptation is not possible. Yet scientists often fail to communicate complex data and results. Effective communication makes STEM research more effective, inspiring society to adapt.

Art and science separated in the 19th century. Today, artists (visual, performing, literary), educators and scientists increasingly recognize the opportunity of much broader, deeper, positive impacts and contributions by reunification. Through arts, humanities and design, we create intellectual and emotional connections to scientific facts, drive personal engagement, and motivate people to action. Artists work as activists, creative researchers and direct communicators of scientific ideas. Furthermore, the importance and the benefits of involving art in STEM education has

been recognized globally in school systems and within the framework of cultural and research institutions.

NSF could explicitly seek proposals that include broader impacts by linking scientists and science with those who communicate issues of climate change science employing: sculpture, film, design, history, painting, data-visualization, architecture. Doing so will allow climate change science to be explored and addressed - in high-visibility public venues. Climate change issues speak to artists and there are examples of high-profile works related to climate migration, large-scale environmental degradation, mass consumption of nature and the landscape in Anthropocene, climate justice, climate and postcolonialism.

Convergent or Transdisciplinary Research

1. Carbon dioxide removal strategies (not necessarily "climate intervention"). I am referring to safe, clean, and functional technologies that exist today that do not have the potential to do more harm than good.
2. Climate modeling of surface albedo modification can be integrated with limited contained on-the-ground albedo measurements of materials on ice, water and snow to predict outcomes of intentional limited-area intervention to slow the melt, and restore, polar ice reflectivity. Safety and materials fate evaluations, proposed different types of deployment on ice, water, and land, can be integrated with materials performance and cost metrics to come to viable solutions to slow climate change devastation, giving time for implementation of longer-term sustainable solutions to decarbonize.
3. Design standards and guidance for resilient infrastructure.
4. Improve forecasts for renewable energy.
5. Intercomparison of existing and ongoing studies.
6. Lightning has recently been added as an essential climate variable by the WMO, so it is only just now being explored as part of the climate change monitoring system.

Future research will require new interdisciplinary partnerships between scientists in atmospheric electricity and those in forest fires as well as permafrost, and other areas.

7. NSF could encourage transdisciplinary/convergent climate-engaged research at a broader scale by incentivizing universities to change their practices. For example, building off the model of the NSF Quantum Computing & Information Science Faculty Fellows, NSF could support faculty hiring in departments and schools in U.S. institutions of higher education that conduct cross-disciplinary climate research and teaching that engages stakeholders, provided they demonstrate that they have promotion & tenure policies that are supportive of such efforts.
8. Plant breeding research combined with geoscience/natural hazards/environmental quality research to optimize green infrastructure/natural climate solutions.

9. Researchers in hydrology, aquatic ecology and environmental engineering could interact and coordinate on this area to address needs.
10. Setting up a unified data portal that pays for validated climate observations using AI to check quality. This would result in immediate creation of a global climate observation data set.
11. The ongoing pandemic might be used as a "pop quiz" to evaluate how well our institutions, infrastructure, leadership and ability to cooperate respond to sudden crisis. Perhaps this is the time for a thorough, transparent, nonpartisan international study of shortcomings and successful novel approaches. The challenges to economies, societies and survival, itself by a deteriorating global climate might be upon us sooner than expected: the traditional solutions of wealth reshuffling, slow bureaucratic response and political maneuvering might not serve humanity's long-term interests. Could the scientific community, with a tradition of organized analysis and teamwork across political borders, offer an open forum and data-based study of effective options to adapt to an inhospitable planet, using the examples of failure and success in adapting to Covid-19?
12. Transdisciplinary science for action: Step up integration of social and natural sciences with engineering and design disciplines and community practitioners around the concept of how future damages from climate impacts (infrastructure, human health, ecosystems, agriculture) accrue without swift mitigation and adaptation actions. The goal would be to move the understanding of how the cost of future climate damages compares to up-front mitigation/adaptation costs from the realm of academics into mainstream decision-making. This would require better integration of many disciplines that can inform society as to the impacts from present and future climate change as well as economic messaging that can better characterize to non-academic communities at different spatial scales the consequence of delayed action. NSF could seed this needed integration.
13. Linking climate modeling to climate risks under a variety of localized low-risk climate intervention scenarios, and economic outcomes (such as insurance payouts) may help in prioritizing research \$ for evaluation and development of better climate interventional solutions for locations at risk.
14. Climate and health vulnerability and adaptation assessment
15. Increase funding for cross-cutting climate informatics initiatives (e.g. EarthCube) to support long-term (i.e. beyond the lifetime of a NSF grant) maintenance of climate solutions data and tools. To facilitate interdisciplinary research, build upon and connect with existing repositories in other disciplines (e.g. UC Santa Barbara's National Center for Ecological Analysis and Synthesis, University of Maryland's Social Data Science Center, USGS' Powell Center).

Data cataloguing:

- Require that NSF-funded data products be submitted to EarthCube along with metadata requirements and methods
- Support dedicated domain expert staff to catalogue the data, log quality control complaints, and support interdisciplinary connections among datasets.

- Example: collate, gather, quality control existing soil carbon datasets

Support for climate tools:

- Stakeholder engagement relies on consistent, reliable tools. There are many existing tools but they have inconsistent spatial/temporal coverage, disciplines are often siloed, and their maintenance is not supported beyond the lifetime of a grant cycle.
- Comprehensive evaluation of existing and in-development tools across climate impacts/adaptation/mitigation spaces
- Identify best performing tools and expand them nationally/internationally
- Allocate resources to maintain tools long-term by dedicated staff
- Example: Incorporate climate impacts projections into existing environmental justice mapping efforts (e.g. EJSCREEN, CalEnviroscreen, Washington Environmental Health Disparities map)

16. Planetary Health research for determining the effect of deforestation, cultural practices, biodiversity loss, and environmental degradation on human health.

Earth and Space Science Research (already within GEO and not convergent)

1. Climate and climate change, weather extremes, earth sciences, remote sensing, disease propagation and transmission dynamics, epidemiology, socio-economics/demographics,
2. Examining and improving the system through which calls for and review of proposals is done. I and many choose to do community science, discovery science, expeditionary science despite this often not fitting the NSF system well. For example, I best know the question to ask and approach to take after I get started with the research. For many of us, sufficient start up funds weren't available at our institutions to have the resources needed for proposal development. Could there be funding for Exploration Grants, similar to National Geographic and with funding for salaries? Nat Geo grants do not provide funds for salary. Can there be a fellows program to fuel a next generation of explorers, across career stages? The wonder of our world is immense and an important part of science communication.
3. Real time climate change event attribution
4. Recharge mechanisms or pathways in aquifers
5. Space deployment of energy generation and transmission systems and capabilities.
6. cryospheric science, soils science, erosion with climate modeling

Education and Training

1. Research training (doctoral, post-doctoral) at the interface of climate science and health, co-funded by NSF and NIH.
2. Public - private partnership to deploy climate training programs for the non-climate scientist and non-scientist professional who wants to do something about climate change but has no education or tools to do so. I am executive director of Climatepedia, a climate education nonprofit. We designed the Climate Literacy Certificate Program, a 12-week program for students and professionals to learn diverse topics about climate change, then create action plans to communicate with and engage in climate action in their communities and networks. Because of a lack of funding for this niche, we compete with "local climate action projects" and "student engagement/education projects" for grants that don't really match our program.
3. Expand the program with Historically Black Colleges and Universities (HBCU), Hispanic Serving Institutions (HSI) and community colleges to increase disadvantaged minority involvement in geosciences by embedding people in regions to find synergies to enhance the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science (INCLUDES) program. This program would accelerate the implementation of a top NSF priority, INCLUDES. The primary role would be to form alliances and partnerships that use research-based collaborative change strategies meant to unite a wide variety of partners to solve a common broadening participation problem. It would include building capacity for leadership and communication among organizations and individuals to create opportunities in STEM education and careers. Creating a collaborative infrastructure would lead to more partners joining the movement, more connections being made, and a chance for collaborative change to lead to expansion, sustainability and scale, with an emphasis on partnerships across organizations from different sectors, such as industry, professional societies, informal STEM organizations and others. INCLUDES shifts away from single-project efforts, and recognizes that complex problems are best addressed through collaborative approaches and shared resources among varying institutions, industry, professional societies and the scientific community at-large. It would be valuable information to have staff from NSF "in the field" to feed information back to the NSF INCLUDES teams, which are the Design Team, the Leadership Team and the Implementation Team, on how this effort is working. Early notice of potential challenges and opportunities would allow NSF to capitalize on this information promptly. Better integration of Advanced Technological Education Centers and Projects (ATE), Innovative Technology Experiences for Students and Teachers (ITEST), and Research Experiences for Undergraduates (REU), would benefit these programs.
4. Related to critical training and career paths, the geoscience community and academic departments should re-examine degree offerings and align them with anticipated workforce trends and climate solutions-related employment opportunities to shape more applied. degree programs.

5. Service learning (e.g. scaling adoption/adaptation of partnering around resilience themes); Education research & implementation as a part of advancing translation (moving from education on earth systems at global scales to education at local/justice/actionable scales that teach students how to engage for systemic change)
6. STEM education for minority grade school children in underserved communities in South Florida. This program was created by Florida International University, but ended due to the lack of funds. Program included a collaboration with the National Park Service to provide field trips/education at park locations. 60 to 80 children received classroom education monthly, and field trips once a quarter.
7. Summer academies/boot camps with certifications/badging to give newly minted graduates training on working with communities/solution science/ etc
8. The issues we face around adapting and mitigating the effects of climate change go beyond just science and technology solutions. From extreme weather events to increased food insecurity to detrimental impacts on human and ecosystem health these solving these challenges requires systems approaches that encompass knowledge not only from science and technology but also from the communities that are directly affected. Climate change needs to be seen as a driver that affects the whole Earth system including the natural and built environment as well as the human system. The solutions therefore must understand and assess the impacts on the entire system. Solutions such as clean energy, more efficient agricultural practices, early warning systems all can be devised but the adoption of the solutions must be done through community engagement and a clear understanding of how culture and tradition will affect the efficacy of these solutions. To realize real progress, we must provide resources that focus on building partnerships between science, technology and society and to support those individuals who wish to engage in transdisciplinary research. At present, the science and technology community lacks the critical skills to effectively engage in co-design of solutions for both adaptation and mitigation. In addition, the populations that are most impacted by climate change are neither represented in the science and technology community nor the decision/policy-making community. These issues point to systemic faults in the STEM enterprise that urgently need to be addressed. There are several steps that should be taken simultaneously to help make much needed progress.
 - a. Dedicated funding needs to be provided to support the science and technology communities to undertake transdisciplinary systems research that encompasses co-design with stakeholders and decision-makers and that address trade-offs and balances among different solutions for adaptation and mitigation.
 - b. The skill set needed for transdisciplinary approaches is not part of mainstream training in higher education and needs to be part of the formal curriculum. There needs to be an international effort to develop the foundation of TD skills and best practices that can be provided to not only students but also professionals working along the research to action spectrum.
 - c. There needs to be a pipeline of job opportunities for those trained in transdisciplinary approaches between higher education, especially in minority serving institutions, and local, regional communities to provide legitimacy of

this approach – basically there needs to be a new science/research pathway. One perfect example of such a program is Global Sustainability Scholars and Fellows which relies on a cohort approach for underrepresented students and early career researchers to engage with international TD projects through the Belmont Forum. This program builds critical networks of these students and researchers that can work together and are likely to be the next generation of science leaders and decision-makers. This program could be easily scaled up to increase the number of students.

- d. The challenges that societies face also go beyond geopolitical borders and require international cooperation to help address truly global issues. While the US has always been a leader in international science and technology, we urgently need productive partnership with other countries that employ transdisciplinary approaches to adaptation and mitigation. To this end, we must fully support the US community to engage in international transdisciplinary coalitions.
- e. The US cannot fund this type of research only at the domestic level, there needs to be a coalition of international funding agencies that span the full spectrum from research to development to realize meaningful change. The Global Forum of Funders is a critical example of national science funders, philanthropy and development aid agencies working together to develop a framework to more efficiently support international cooperation in transdisciplinary systems approaches to adaption and mitigation.

Several approaches could be used to reach these goals. GEO should set aside dedicated funding to build on the efforts currently undertaken through the Belmont Forum but provide a more robust training and coordination among these international research projects. In addition, there needs to be a coalition of US agencies, such as those engaged in USGCRP to develop more inclusive research programs using the TD approach and to incorporate those into current international efforts such as Belmont Forum, Inter-American Institute for Global Change Research and Future Earth. GEO needs to ensure that the Global Research Council makes climate change adaptation and mitigation a research cooperation priority and it should push the use of existing mechanisms like the Belmont Forum to develop new innovative partnerships. An increased investment of \$10M USD per year would adequately support the development of these initiatives which would leverage existing research partnerships and mechanisms and provide a new approach to developing the next generation and future workforce that can help solve critical challenges and realize opportunities for climate change.

- 9. There is a large "middle ground" in environmental education that seems to get left out. So much is geared towards either R1 universities, or community colleges/etc. However, the majority of those going into environmental fields professionally - either via grad school or directly into the workforce - come from the large number of primarily-undergraduate institutions. I know that e.g. the NSF has this category of RUI. But those are grants that are submitted with the R1 schools, but get shuttled off a bit to the RUI funding pool. Those of us at primarily-undergrad schools have these heavy teaching loads - teaching the majority of future environmental workers - but don't have time for creating these massive proposals. It's a classic Catch-22 situation. I have

advocated for years for national agencies to have a category of "microgrants" that are e.g. \$10k and below. For primarily-undergrad schools and community colleges, that would make a tremendous difference in our work to educate future climate scientists.

10. Training on when and how to engage stakeholders / community members in research. The Climate Adaptation Science Centers are great at this, I've found that very few of my colleagues know about them
11. Training students in evaluating and risk analysis in complex systems - this does not have to be mathematical, but to train students to consider consequences in other sectors/potential feedbacks
12. Create traineeship, modeled after IGERT and other graduate educational efforts, but designed to bring scientific ways of thinking, not just expertise, to bear on solving specific questions in communities. Program with the ability to address a broad range of questions, draw on network of expertise, ability to address new questions posed by small business, non profits, education, etc.
13. Support curriculum for climate change mitigation (e.g. renewable energy penetration, carbon removal technologies, life cycle assessments) with particular funding and scholarships for students from underserved communities
 - a. Also think we need climate justice curriculum, or curriculum that helps students think about how to make structural change instead of individual action, or knowing problem but not change roles.

Environmental Justice and Equity

1. NSF research funds could be re-focused on community-engaged research/outreach activities rather than fundamental science discoveries - right now climate action is urgent and more important than fundamental research, if we are to achieve the goals we have set for 2030.
2. Collaborative research in support of Tribal environmental/climate change priorities. This is underfunded and patchy, and could be better coordinated! Tribal resource management networks are strong across the US, and the Tribes are often interested in using cutting-edge research techniques (more than state or federal agencies are). Tribal priorities are sometimes already spelled out in available climate change adaptation plans or other reports. (But of course any project would start with listening!)

Partnership or Community Priorities

1. Citizen science and community-engaged research across different regions and countries when both communities and researchers can learn from each other
2. NSF working with international organizations

3. Combining existing community science fellowship and science policy fellowship to bring community science facilitators to rural communities to address the many environmental science issues facing many rural and small communities across the country who lack access/funding for scientific resources, importantly building trust by remaining in contact over long periods, working to bring external science resources to those small communities.
4. Connecting municipal officials/on the ground workers with scientists/researchers to make science actionable - these groups are looking for help with modeling climate impacts and cost-benefit analyses of solutions they should implement and researchers work will be used in real-time!
5. Integration and expansion of local community watershed projects, land trusts, restoration efforts and protected areas.
6. Connecting applied community projects to capacity building work to change policies. More rain gardens are important to mitigation, but don't address structural challenges like zoning, poor land use planning.
7. Rejuvenate the Resilience Dialogues supported by the Obama administration
8. The Urban League of Cities has been gathering to discuss and share best practices to create and implement resilience plans. They do not have a way to easily map zoning and land use regulations with demographic data to identify high risk areas and populations. They are doing this piecemeal, each on their own. Like above, it would be great to have a standardized way to look at this and software tools for them to use. Big cities are further along, but smaller ones don't have the staff or resources to do this. ULI is also a partner in this effort, mostly as a convener.
<https://americas.uli.org/resilient-cities-summit/>
<https://www.nlc.org/initiative/sustainability-and-resilience/>
<https://resilientcitiesnetwork.org/rcities-nlc-partnership-accelerate-urban-resilience/>
9. Promote citizen science organizations and activities that bring citizens, scientists, and policymakers together to develop climate policies and programs.
10. Create forums in which artists, humanists, faith leaders, and activists working on climate change can engage with scientists and policymakers.

Partnerships

1. Accelerated technology transfer of climate solutions out of academia and into civil society / Modernize STEM graduate training to prepare PhD students for the multitude of promising non-academic careers and the skills required to thrive in them
2. Funding efforts and partnerships. In my experience, funding for programs for marginalized communities have been dependent on state available funds, and in Oklahoma, these funds tend to be applied to non-marginalized communities.

Otherwise, universities study environmental issues within marginalized communities in Oklahoma, but these research projects are dependent on funding available and funding that can be applied for. It would be beneficial if there could be funding for marginalized communities to address issues, or more accessible funding for researchers to do research within these communities, possibly with the added component of adding a science communication aspect to it. Also, if partnerships were encouraged between communities, organizations, agencies, and universities.

3. Large scale forest restoration in the tropics
4. This one has been floated a lot, but greater coordination between NSF and NIH, and perhaps NSF and EPA, including more joint RFPs, could be very helpful.
5. Establishment of regional Infrastructure Councils comprised of public- & private-sector utility firms aligning with local government decision-makers on resilient, green & smart systems

Policy

1. Probably the United Nations. It is THE global organization that brings together government organisations and important NGO's such as the International Science Council (Including CODATA and the World Data Service) in a policy context. Through the 17 Sustainable Development goals, the UN puts climate research in the context of grand challenge issues for our planet.
2. Restoring coastal ecosystems (blue carbon systems) to reduce carbon pollution--this needs to be coordinated across the entire country to ensure the fastest progress and cooperation across regions.
3. Encourage and support a greater number of social and behavioral scientists to become involved in IPCC, UNFCCC, and other international climate change bodies.
4. integrate sociology to geosciences

Science Societies

1. Community participation in monitoring and adapting to climate change
2. Coordinate work across scientific societies? Societies, including some that have historically been focused on extractive industries are seeking ways to support the energy transition. Some societies such as AGU and AMS have climate science as part of their natural scope. Others are involved through critical mineral needs for energy infrastructure or the like. Provide an opportunity for societies to converge and work together on climate response and energy transition? Note that AGI is a Federation of the geosciences societies, with 50 or so member societies
3. Coordination of DEI efforts across societies.

4. Soil Carbon - ideally, a human genome project equivalent for soil carbon - support and infrastructure for widespread accelerated collaboration and knowledge sharing across fields related to soil carbon (agronomy, geoscience, biology, economics, engineering)
5. Establish a body of climate change representatives from major scientific and professional societies to exchange ideas and collaborate on interdisciplinary initiatives.
6. Quality data is important for communities and government at different levels to take actions in response to the climate crisis. Thus, climate service is fundamental component of the whole process. In a recent public hearing hosted by House Appropriation Committee, Subcommittee on Commerce, Justice, Science, and Related Agencies, NOAA leadership has testified on the increasing risks of climate change and the importance of climate services. The hearing has demonstrated the need of improved climate service to enable local communities and states to take sensible actions via data. Earth science community is blessed with data and we all believe this data are extremely valuable. But the reality is that communities and governments are often unable to get the information they need effectively because of how the data is scattered across different portals and it is even time consuming for researcher to get necessary data for our own research. There needs to be significant investment on providing climate services and all relevant data in a central, accessible, and easy-to-use location to *make data matter*. Researchers should not be data keepers but a connector/enabler to amplify the value of climate services. This coordinated effort could yield huge impact instead of individual small progress.
7. Community science consortium - opportunity for multiple societies including multiple disciplines. It would be an opportunity to provide multidisciplinary support to communities whose priorities are not limited to one discipline and streamline community science efforts
8. Restoration, rehabilitation, reuse and repurposing of oil and gas field infrastructure and materials.

Relevant References

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- 125 Participated in some form
 - 78 Contributed to ideas form
 - 82 Attended workshop 1
 - 28 Attended workshop 2
- 114 in the Earth and space sciences
- 22 Early career
- 9 Students

Other Disciplines Included:

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- JEDI and Community Organizations: 4
- Urban Resilience and Risk Management: 3
- Architecture and Built Environment: 3
- Municipal Government: 1
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