Cooperative Institute for Earth System Research and Data Science (CIESRDS)

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Total Federal Funds Requested:
$565.8 M (ceiling)

Award Period:
September 1, 2022 - August 31, 2027

Throughout this proposal, “CIRES” refers to the CU Boulder-based research institute funded primarily by the National Oceanic and Atmospheric Administration (NOAA) since 1967, and also by other external grants and CU Boulder. If this proposal is funded, CIRES will remain a University of Colorado Research Entity, and the Cooperative Institute for Earth System Research and Data Science, or CIESRDS, will comprise the core of CIRES, representing a new cooperative relationship with NOAA that builds on our 54-year partnership.

Table of Contents

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1. Abstract

CIESRDS seeks to fulfill NOAA's vision of "healthy ecosystems, communities, and economies that are resilient in the face of change." We propose a comprehensive, innovative, and flexible research program to achieve NOAA's vision and goals, with a focus on Earth system research and data science. CIESRDS will employ world-class researchers to conduct science in service to society and in partnership with NOAA. CIESRDS will be supported by a robust infrastructure committed to equity, education, and outreach. We will be able to respond quickly to help society meet the rising challenges of environmental change and to inform proposed solutions.

The need for cutting-edge Earth system research and data science—which CIRES has conducted and CIESRDS proposes here—becomes more and more apparent every year. Recent CIRES work has been essential to informing leaders at all levels on options for adaptation to droughts, floods, and wildfire; for improving weather forecasts and air quality; and for analyzing the consequences of energy transitions. Our science has even informed the societal response to COVID-19, a disease that spreads in the atmosphere via aerosol.

CIRES has collaborated with NOAA for more than 54 years, with staff functionally integrated within the agency and integral to its Earth system research and data science successes. We have made NOAA weather forecasts better, submarine navigation more accurate, and have been leaders in applying AI and big data analytics to many areas of NOAA work. We have pursued and refined innovative ideas that changed the ways NOAA has conducted operations in the Boulder-based laboratories and centers. The unique alignment of expertise, mission, and capability of NOAA and CIRES/CU Boulder has helped make CU Boulder the #1 university in the world for both Earth Science and Atmospheric Science.[1]

CIESRDS will build from this experience to do more in support of NOAA's mission, conducting innovative science that makes navigation and communication safer; saving lives and property with research that improves forecasting at all scales; and prioritizing work that builds society's resilience to environmental change. Our proposed efforts in this area are described Section 3.B., divided into 8 interconnected themes: (1) Future Atmosphere; (2) Climate Science and Prediction; (3) Earth System Data Science, Stewardship, and Application; (4) Regional Science and Applications; (5) Scientific Outreach, Education, and Diversity; (6) Space Weather Science and Prediction; (7) Weather Research and Forecasting; and (8) Science and Predictions to Support Ecosystem Research.

Importantly, CIESRDS will expand upon CIRES' education, outreach, and diversity experience: We train the agency's and the world's next-generation Earth system and data scientists. We work to ensure our science is useful and used by educators, decision-makers, journalists, and the general public. And we engage a diversity of people and perspectives to promote scientific excellence and integrity. Our commitment to and success in world-class science, broadening the impacts of that science, and track record of funding success within and beyond NOAA make CIESRDS an investment that will provide excellent and demonstrated returns.

2. Results from Prior Research

Established in 1967 by a handful of scientists and at about 830 people today, CIRES is the largest and one of the oldest of NOAA's cooperative institutes, and our mission is tightly aligned with the priorities of the agency and the NOAA Boulder laboratories. In collaboration with NOAA, we focus on producing world-class ***science in support of society,*** and our people work side-by-side with federal colleagues to this end. CIRES scientists have been integral to the success of NOAA's Boulder enterprise.

In the last 5 years, CIRES scientists have published more than 3,500 peer-reviewed papers, nearly half of those from our NOAA-based work. Research led and supported by CIRES Earth system and data scientists has appeared in every annual NOAA Science Report and has been recognized with countless Gold, Silver, and Bronze Department of Commerce medals. CIRES scientists have annually earned top global honors, for example for highly cited researchers, and have contributed to countless national and international assessments. CIRES has been very successful at obtaining external funding for research that is often well-aligned with the NOAA mission. Collectively, this external, non-cooperative agreement funding totaled $206M in the last 5 years (FY17-FY21). For example, CIRES' researchers obtained $4.4 M in direct support from the National Science Foundation (NSF) and the Department of Energy (DOE) to co-lead the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) mission to understand the changing Arctic. MOSAiC supports NOAA's Arctic coastal and sea-ice forecasting, weather forecasting in the region and elsewhere, and global climate understanding. In another example, CIRES' Earth Lab has won external grants totaling $13 million in the last 4.5 years to apply big data analysis to Earth systems data to help society adapt to a changing world. Such work, funded by others, advances NOAA's mission and provides the agency with scientific and public visibility, multiplying NOAA's return-on-investment.

CIRES' areas of expertise developed in large part from our years of partnership with NOAA. Below we highlight a few CIRES achievements from the last five years, as aligned with our current guidance document, NOAA's Next-Generation Strategic Plan.[2] Much more detailed information is provided in our annual reports to NOAA,[3–7] which describe the results of CIRES' most recent research awards with NOAA, listed in Table 1.

Weather-Ready Nation

CIRES has supported research leading to a Weather-Ready Nation, saving lives and property, supporting forecasters, and increasing resilience. With federal colleagues, CIRES researchers:

- Developed, improved, and operationalized the High-Resolution Rapid Refresh (HRRR) model, including High-Resolution Rapid Refresh-Smoke (HRRR-Smoke) model, helping users anticipate the air quality impacts of wildfire smoke.[8,9]
- Led verification work on icing, turbulence, and convection forecast products, supporting aviation.[9,10]
- Improved space weather forecasts by operationalizing the Whole Atmosphere Model (WAM)-Ionosphere Plasmasphere Electrodynamics (IPE) model[11] and providing space weather information to the international civil aviation community.[12]

Climate Science, Adaptation, and Mitigation

CIRES science has improved understanding of Earth's changing climate, informing society and allowing decision-makers to anticipate and respond. With federal colleagues, we have:

- Led an international mission to understand how sea-ice loss is impacting the coupled ocean-ice-atmosphere system of the Central Arctic Ocean, with global reverberations.
- Discovered substantial unreported emissions of chlorofluorocarbon-11 (CFC-11), an ozone-depleting substance, and tracked declining emissions after China took action.[13–15]
- Produced calibrated measurements of greenhouse gases, data that are foundational to NOAA's efforts to track and report global greenhouse gas (GHG) distributions and trends.[8,16]
- Provided relevant science that directly helped communities, states, and utilities decide on appropriate adaptation actions in the face of drought, flooding, wildfire, and changing extremes.
- Developed the Living Blended Drought Product, documenting U.S. drought conditions for the last 2000 years, informing our understanding of future drought risk.[17,18]

Commerce, Transportation, Engagement

CIRES has helped NOAA meet the complex needs of stakeholders by producing and sharing data and knowledge. With federal colleagues, our scientists:

- Developed and refined Forecasting a Continuum of Environmental Threats (FACETs), to help forecasters better understand threats like tornadoes, hail, and extreme rainfall.[19,20]
- Developed visual displays of NOAA's Earth science data for Science On a Sphere® (SOS) and SOSx Mobile®, engaging millions of people annually, and increasing scientific understanding.

Science and Technology Transfer

CIRES has worked to understand the holistic Earth system to serve the needs of decision-makers. With federal colleagues, our scientists:

- Produced the 2020 World Magnetic Model (WMM), used daily for military, airline, mobile phone, and other navigation needs.[21]
- Compiled coastal geophysical data for the U.S. Extended Continental Shelf Project, to document the extent to which the Nation may claim rights to natural resources.[22,23]
- Extended the Coupled Arctic Forecast System (CAFS) domain to support the National Weather Service (NWS) Alaska Sea Ice Program and the MOSAiC campaign.[24]

Table 1: CIRES Prior Research Awards with NOAA

Title	Award #	PIs	Start/end dates	Total Funding
CIRES Cooperative Agreement	NA17OAR4320101	Waleed Abdalati	9/17-8/22	$235,915,231.72*
CIRES Cooperative Agreement	NA15OAR4320137	Konrad Steffen, Waleed Abdalati	9/12-12/18	$74,786,919.29
CIRES Cooperative Agreement	NA12OAR4320137	Waleed Abdalati	9/12-12/18	$108,804,151.92

* As of December 31, 2021

3. Project Description

3.A. Goals, Expected Accomplishments, and Alignment with NOAA

The *overarching goal* of the proposed new cooperative institute, CIESRDS, is to support NOAA with Earth system research and data science on topics of significant societal importance. With the proposed innovative and flexible research program, CIESRDS can help society respond to meet the urgent needs of a changing world. The following are the goals of CIESRDS:

- Conduct high-quality Earth system research and data science in collaboration with and service to NOAA to support society's resilience to environmental change,
- Train and inspire a diverse and skilled future Earth system and data science workforce for NOAA and beyond,
- Grow Earth system research and data science literacy in learners of all ages,
- Serve the general public and decision-makers with information that fosters resilience to changes in the Earth system, and
- Provide the robust scientific and administrative infrastructure to run a cooperative institute cost-effectively, to successfully fulfill NOAA's needs and objectives. This infrastructure will support growth, given CIRES' trajectory of success in external funding.

CIESRDS' vision is to be an international leader in conducting cross-cutting environmental research of the highest quality while bridging fundamental science and service to society. We will build leaders, scientists, communicators, and teams dedicated to developing sound and trusted information to address environmental challenges. We will embrace a positive and inclusive culture, recognizing that CIESRDS thrives when our people do. Proposed CIESRDS projects described in more detail below will help NOAA achieve the goals outlined in three key strategic documents. Here, for each NOAA goal, we provide one or two examples of proposed CIESRDS work that aligns. Section 3.B. describes proposed work in greater detail, and Table 2 depicts overall alignment visually (highlight colors correspond to colors in the table).

3.A.1. 20-year NOAA Research Vision (2005)

Proposed CIESRDS work supports all four elements of the Research Vision. For example:

- **Ecosystems**: CIESRDS bathymetric and acoustic sounding work in coastal zones will be critical for evaluating fisheries habitat and populations (Section 3.B.3.);
- **Climate**: Our proposed work will improve scientific understanding and modeling of aerosol-cloud-climate interactions (Section 3.B.2.);
- **Weather and Water**: CIESRDS scientists will investigate and improve regional water and drought forecasting (Section 3.B.4.); and
- **Commerce and Transportation**: Our proposed work includes updating the WMM, which is critical for most navigation (Section 3.B.3.).

3.A.2. NOAA Next-Generation Strategic Plan

CIESRDS' proposed work will align with all four goals and all three "enterprise" objectives described in this document. For example:

- **Climate Adaptation**: We propose several lines of research to improve subseasonal-to-seasonal (S2S) prediction (Sections 3.B.1, 3.B.2, 3.B.4, and 3.B.7);
- **Weather-Ready Nation**: We will improve fire weather and other hazard prediction with tool-development and improvement projects that support forecasters (3.B.3, 3.B.4, 3.B.7.);

- **Healthy Oceans**: We propose research to improve marine heatwave forecasting to help plan for impacts, including to the habitat of commercially important fish (Section 3.B.8.);
- **Resilient Coastal Communities and Economies**: We plan to build and update coastal digital elevation models (DEMs) to better predict tsunami runup (Section 3.B.3.);
- **Science & Technology tech enterprise**: We propose to apply machine learning (ML) to analyze and extract the most important Geostationary Operational Environmental Satellite (GOES) satellite data for assimilation and forecast improvement (Section 3.B.7.).
- **Engagement enterprise**: We propose to engage with diverse audiences—including Tribal Nations and colleges, Congress, journalists, educators, and decision-makers (Section 3.B.5).
- **Organization & Administration enterprise**: We propose an efficient, cost-effective Business Plan (Section 3.E.) that will support a modern, safe, and compliant infrastructure.

3.A.3. NOAA 20-Year Research & Development Vision Areas

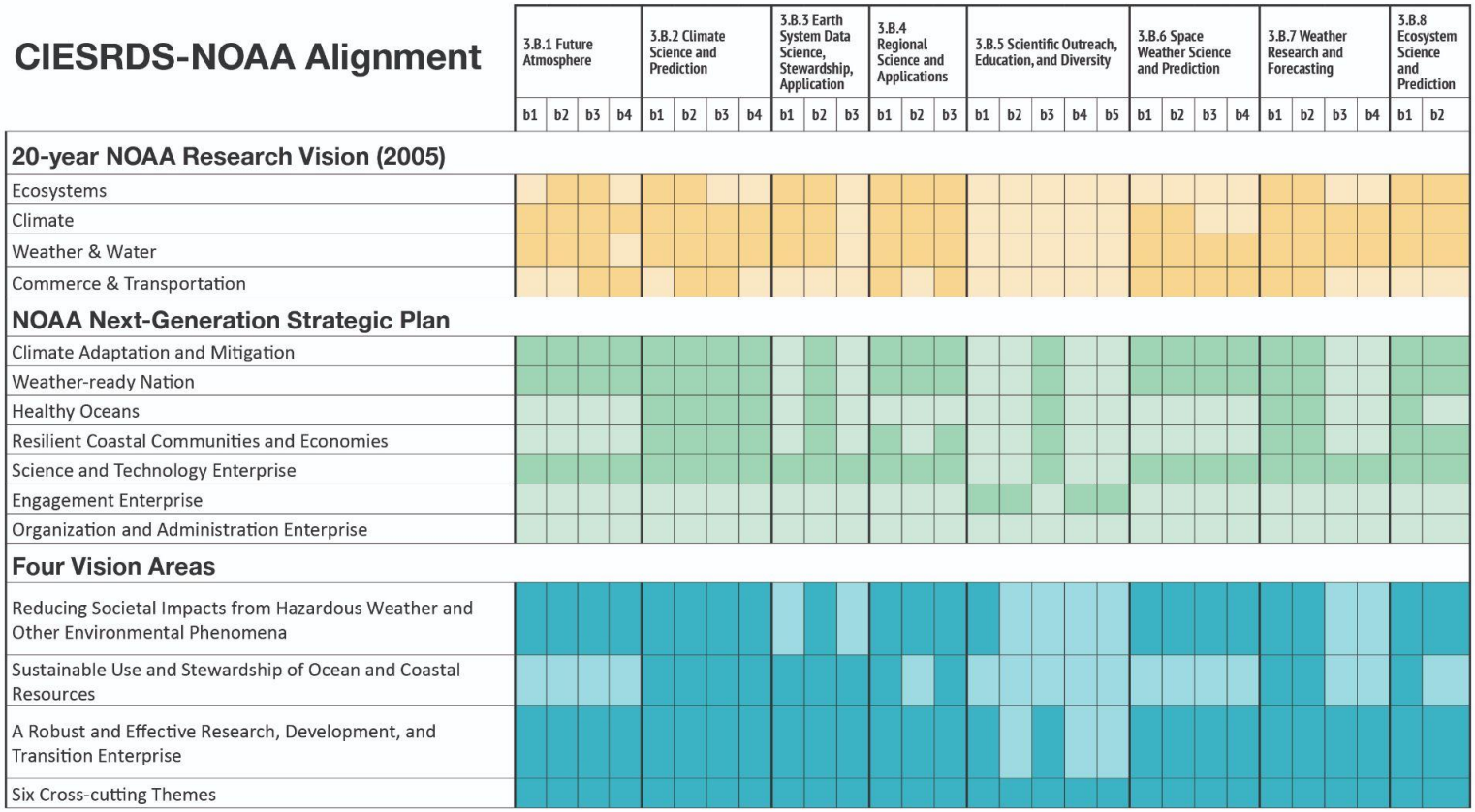
Proposed CIESRDS work aligns with the three vision areas in this document, and all the cross-cutting themes except 'omics. For example:

- **Reducing societal impacts from hazardous weather and other environmental phenomena:** CIESRDS will serve the international aviation community with improved space weather forecast products and will use observations and models to identify causes of western U.S. droughts.
- **Sustainable use and stewardship of ocean and coastal resources:** CIESRDS will provide curated Arctic sea-ice data and products that serve the marine navigation and safety needs of indigenous communities, the fishing industry, and others.
- **A robust and effective research, development, and transition enterprise**. All proposed CIESRDS work aligns with this theme, including the transition of key research to operations. (Research Themes Section 3.B.)
- CIESRDS' proposal includes significant research contributions and innovations in **six cross-cutting themes**: Climate Science (Section 3.B.2.), Ecological Forecasting (Section 3.B.8.), Polar Science (Sections 3.B.1., 3.B.2, 3.B.3., 3.B.4., and 3.B.8.), Uncrewed Systems (UxS) (3.B.2. and 3.B.4.), AI and ML (Sections 3.B.1., 3.B.2., 3.B.3., 3.B.4. and 3.B.7.), and Big Data (Sections 3.B.3., and 3.B.8.).

Proposed CIESRDS work also aligns with all elements of NOAA's Education Strategic Plan[25] and the agency's Diversity and Inclusion Strategic Plan.[26] In support of education goals, for example, CIESRDS will support the citizen science app-based program CrowdMag, to help NOAA map Earth's magnetic field; we will evaluate, curate, and disseminate K-16 climate curricula; and we will work with NOAA's Educational Partnership Program/Minority Serving Institution (EPP/MSI) faculty to offer a portfolio of well-calibrated projects for fellows and other participants. Many elements of the Diversity plan will be integral in CIESRDS. For example, we will run a mentoring program and support early-career and new staff with trainings that include leadership development; we will track workplace culture among NOAA-based employees, with annual surveys and take actions based on the results; and we will amplify our justice, equity, diversity, and inclusion (JEDI) and belonging efforts through collaboration with partners, including NOAA, with regular communications from leadership, and by tracking and evaluating progress.

Table 2: CIESRDS-NOAA Alignment

CIESRDS-NOAA Alignment



3.B.1 Future Atmosphere
- b1 Aerosols
- b2 Chemistry and Climate
- b3 Air Quality
- b4 Earth Radiation Budget and Climate Intervention

3.B.2 Climate Science and Prediction
- b1 Boundary Layer Observations and Processes
- b2 Predictability of Extremes, Trends, and Climate Variability
- b3 Attribution Research
- b4 Tropical-Extratropical Interactions

3.B.3 Earth System Data Science, Stewardship, and Application
- b1 Properly Managed Data
- b2 Data Science and Exploitation
- b3 Modern Data Access Systems

3.B.4 Regional Science and Applications
- b1 Hydro-meteorology
- b2 NIDIS
- b3 Polar Processes

3.B.5 Scientific Outreach, Education, and Diversity
- b1 Improving Public Understanding of Science
- b2 Postdoctoral and Visiting Scientist Programs
- b3 Harnessing New Technologies: Artificial Intelligence, Machine Learning, Big Data
- b4 Supporting Graduate Education and Other Early Career Scientists
- b5 Improving Diversity, Inclusion, and Equity in the Workforce

3.B.6 Space Weather Science and Prediction
- b1 Observations
- b2 Model Development, Validation and Evaluation
- b3 R2O2R: Space Weather Testbed
- b4 Modernizing SWPC's Space Weather Forecasting Office

3.B.7 Weather Research and Forecasting
- b1 Improved Modeling Capabilities
- b2 High-Impact Weather
- b3 Data Assimilation
- b4 Computing and Disseminating Tools

3.B.8 Ecosystem Science and Prediction
- b1 Climate Impacts on Marine and Coastal Ecosystems
- b2 Climate and Terrestrial Ecosystems

This table depicts how proposed CIESRDS work aligns with three key NOAA guidance documents. Darker areas indicate direct alignment, e.g., aerosol research described in Future Atmospheres (3.B.1 project b1) addresses directly the NOAA Research Vision for ecosystems, climate, weather, and water and commerce and transportation. Lighter areas indicate indirect alignment, e.g., our proposed work to increase and support the diversity of our workforce (3.B.5) indirectly improves scientific endeavors for all topics under the NOAA Research Vision.

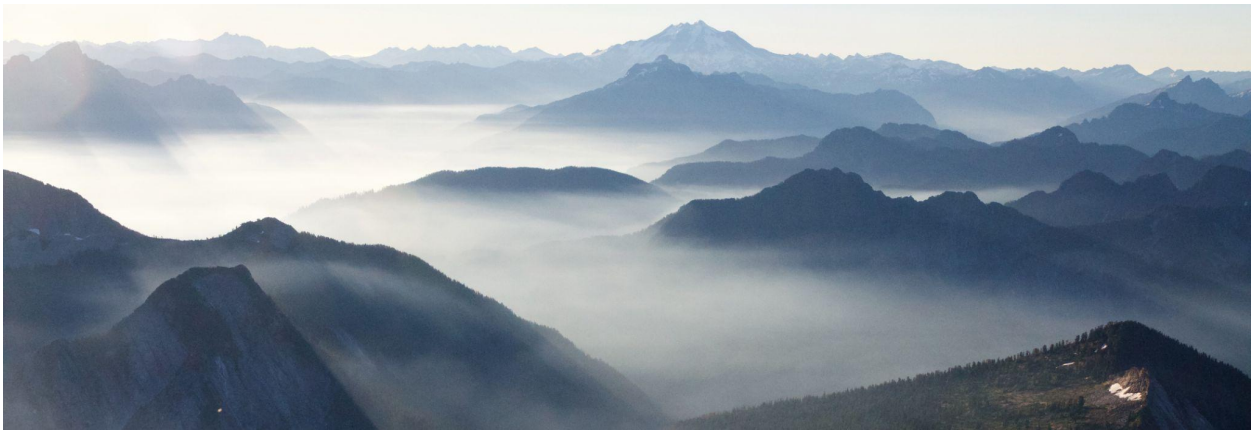
3.B. Research Themes

We propose to address the goals and priorities specified in the Notice of Federal Opportunity (NOFO) with a comprehensive series of integrated research programs described below to produce world-class Earth system research and data science—in service to society and in close collaboration with NOAA. The research program described here is sweeping in scope, but **proposed individual research projects should be considered *examples* of what we can do.** If funded, CIESRDS will work with NOAA to design annual workplans that ensure our research agenda remains ambitious, innovative, and achievable and that it reflects the current priorities of our NOAA partners.

Our proposal is highly flexible. As national Earth system research and data science needs evolve, CIESRDS will respond, both through our collaboration with NOAA and through other sources of external funding to complement our NOAA portfolio. Like CIRES, CIESRDS will be highly connected in Colorado's collaborative Earth system research and data science community; this research network enables quick response to needs and efficient use of federal and other resources.

We organize CIESRDS' proposed work to align with the NOFO, but it is worth noting that many of the proposed efforts in one theme are relevant to others, too. Threaded throughout the activities proposed below are the tools we use and plan to continue using, in support of NOAA's Office of Oceanic and Atmospheric Research (OAR); National Environmental Satellite Data and Information Service (NESDIS); National Weather Service (NWS); and Office of Education:

- Cloud-based data and tools that enable seamless collaboration and sharing of environmental data and other assets
- AI—including ML—to innovate and increase the efficiency of data-intensive research and operations
- Fieldwork, including leadership of regional, national, and international campaigns
- Instrument development and deployment
- Laboratory studies
- Remote-sensing innovations, including instrumentation and analysis, and
- Modeling expertise and tools, including in the field of data assimilation



Full images, captions, and credits are provided in Appendix 9.

3.B.1. Future Atmosphere

3.B.1.a. Overview

Atmospheric composition drives climate change, air quality, and stratospheric ozone depletion, and in collaboration with NOAA, CIESRDS will tackle several relevant research topics to better anticipate the future atmosphere and its implications for society. We propose projects under four topics relevant to this theme: Aerosols, Chemistry and Climate, Air Quality, and Earth's Radiation Budget and Climate Intervention. This research will require instrument development and use, intensive field campaigns, continual monitoring efforts, laboratory experiments, integration of observations with models, and development and improvement of prediction models. Proposed CIESRDS work in this theme will target the surface through the stratosphere and will draw on state-of-the-art tools such as ML and other sophisticated analysis techniques. We will produce timely, accurate, and usable predictions of atmospheric composition relating to changing emissions (eg, wildfire, vehicular), the health of the stratospheric ozone layer, and the planet's radiation budget that will serve NOAA's mission.

3.B.1.b. CIESRDS Proposed Work for 2022-2027 and Beyond

3.B.1.b.1 Aerosols

CIRES Background

Atmospheric aerosols make important, complex contributions to Earth's climate system, to air quality, and to impacts on public health and the environment. CIRES and NOAA together are leaders in aerosol science, from the development of instrumentation to field and long-term monitoring deployments to models across scales. *In-situ* measurements of the distribution and properties of aerosols and their precursors on all scales are critical to improving satellite remote sensing, model representation, and understanding of their impacts on climate and air quality. In recent years CIRES scientists and NOAA collaborators have improved our understanding of new particle formation and resulting radiative effects,[27,28] the properties and global distributions of different aerosol types,[29–34] aerosol optical properties,[35–37] and aerosol formation as a source of poor air quality.[38,39] These studies have improved aerosol representation in global models,[40,41] led to recommendations for improving air quality and provided data necessary for calibrating and validating satellite retrievals.

CIRES scientists have played vital roles in large-scale field campaigns, such as ATmospheric Tomography (ATom), and Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ). CIRES and NOAA collaborative analyses stemming from those missions have elucidated the global distribution of aerosols (e.g.,[29,32,42–44]), as well as their influence on local and regional scales.[30,45–47] Many of these advances are the result of innovative instrumentation development that has been driven or heavily supported by CIRES efforts.[48–55]

CIRES scientists lead the NOAA Federated Aerosol Network (NFAN) sites,[56] which provides a rich source of data for analysis: at least 45 peer-reviewed papers using NFAN data were published between 2017-2021. The cohesiveness of the NFAN data has allowed for comparison across multiple stations and contribution to wider analysis efforts on global trends and climatologies (e.g.,[57,58]). We have been particularly active in the evaluation and impact of aerosol absorption and model evaluation (e.g.,[59–61]). The NFAN has continued to expand, with eight sites added since the start of 2017. The data from a new site near Boulder that CIRES oversees for NOAA are being analyzed to understand the impact of wildfires on combustion gas and aerosol properties during the extreme 2020 wildfire season[62] and to evaluate the PurpleAir sensor as a low-cost instrument to measure aerosol light scattering.[63]

CIRES scientists have also contributed key research activities to address the uncertainties associated with aerosol-cloud interactions using airborne in-situ measurements, satellite and surface-based remote sensing, and numerical models (e.g.,[64–66]). We have shown that an improved understanding of the mutual role and co-variability of aerosol and meteorological drivers on cloud formation, evolution, and organization is essential for our understanding of aerosol-cloud forcing and cloud feedbacks.[67,68] Our excellence in modeling aerosol-cloud-radiation interactions with large-eddy simulations has led to new process-level insights (e.g.,[69–71]). Our modeling activities have expanded to encompass modeling at the mesoscale,[72] and even the global scale, by advancing the representation of clouds in climate models.[70,73]

Future work of CIESRDS

CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Move an aerosol size distribution instrument from Colorado to the South Pole in a collaboration with the Finnish Meteorological Institute, to estimate the geographical extent of variations in aerosol size distributions, optical properties, and cloud condensation nuclei.
- Use observations from the NFAN and other *in-situ* networks to evaluate global models. To improve model parameterizations of aerosol, we will analyze aerosol climatologies on daily-to-annual time scales and also how well models simulate the observed covariance of aerosol optical properties.
- Develop a process-level understanding of aerosol-cloud interactions, especially in shallow cloud systems. In these efforts, we will explore microphysical and radiative influences of biomass burning aerosol and mineral dust on shallow clouds (e.g.,[74]), leveraging data acquired during field campaigns (e.g., Atlantic Tradewind Ocean-Atmosphere Mesoscale Interaction Campaign or ATOMIC).
- Use new computational tools to investigate the physical and chemical interactions of aerosols in the atmosphere, for example, the state-of-the-art large eddy model developed by NOAA and CIRES, which features a three-dimensional sector model covering a large domain and resolves both 100-m scale turbulence and planetary-scale circulations. We will

also use AI as a proxy model to foster our understanding of aerosol-cloud interactions.[75–77] An important planned outcome of this work is to serve the solar renewable energy community with research that addresses the effect of clouds on surface radiation.[66,77]

- Develop and modify instrumentation to measure key aerosol properties. We plan to improve black carbon-detecting instrumentation to target the stratosphere for the first time in over a decade and to develop a new spectrometer to quantify multiple trace species never before measured in the stratosphere. We will also expand the use of aerosol optical sizing instruments in on-ground and balloon-borne networks. We will extend aerosol composition measurements to smaller sizes and expand measured gas-phase species relevant to aerosol formation.
- Use airborne, ground-based, and ship-borne platforms to measure the size distribution, composition, and optical properties of atmospheric aerosol to better understand sources, atmospheric processing, and impacts on radiation. This work, which will involve several field campaigns, will focus on the role of dust aerosol as ice-nucleating particles, the time-dependent radiative properties of biomass burning aerosol, and the sources and climatic relevance of newly formed particles. It will also enable satellite and model validation, including air-quality and cloud modeling, and importantly, it will also inform assessment of the Earth radiation budget and hypothetical strategies for and detection of climate intervention.

3.B.1.b.2 Chemistry and Climate

CIRES Background

CIRES has led key research activities associated with the chemical and physical processes that impact climate and atmospheric composition. CIRES scientists embedded within the NOAA Global Monitoring Laboratory (GML) have led and contributed to efforts to understand changes in and monitor key climate-driving constituents, including GHGs, water vapor (WP), and ozone. For over 40 years, we have been partners with NOAA in conducting global monitoring of GHG levels with consistent, calibrated air composition measurements from surface, tower, balloon, aircraft, ice core, and firn (compacted snow layer) air sampling. These observations are archived and widely disseminated to support the scientific analyses of GHG trends; the estimation of sources and sinks (e.g.,[78–84]); and to estimate GHG direct climate forcing. CIRES researchers have been key contributors to these efforts, and have provided unique GHG calibration, measurement, and data analysis capabilities that serve multiple partners (National Aeronautics and Space Administration (NASA), NSF, DOE, universities) and international collaborations.[85–89]

CIRES scientists have collected and quality-assured data from Dobson, Brewer, ozonesonde, and surface ozone observing systems; validated satellite records; and produced analyses of stratospheric and tropospheric ozone changes over the past three decades in the northern/southern polar regions, midlatitudes, and in the tropics.[90–95]

We have studied the interannual variability in the dramatic ozone depletion spring events over Antarctica.[96–98] Such analyses relied on GML global observations of ozone, ozone-depleting gases in the troposphere and projections for the stratosphere, assessment of levels of halogens in the oceans, polar snowpacks, and terrestrial ecosystems, and aerosol characteristics near the surface.[99,100] These ozone datasets have been used by the international community as part of several UN Environment Programme/World Meteorological Organization (UNEP/WMO) Ozone assessments (stratospheric ozone) and the Intergovernmental Panel on Climate Change (IPCC)

reports (tropospheric).[101–106] CIRES ozone experts have used statistical models and global chemistry-climate models to evaluate impacts of natural variability (i.e. El Nino/La Nino Southern Oscillation, quasi-biennial oscillations (QBO), stratosphere-troposphere exchange), and anthropogenic emissions on changes in tropospheric ozone and air quality.[107–112]

Since 1980, CIRES scientists have measured profiles of WV at least monthly at Boulder, Colorado, by balloon-borne frost point hygrometers (FPHs) designed and built at GML to monitor WV abundance in the upper troposphere/lower stratosphere (UTLS).[113] The FPH measurements of upper atmospheric WV have provided calibration and validation data for several satellite-based WP sensors.[114–116]

CIRES researchers have contributed to other measurements of ozone-depleting trace gases, providing key measurements for several international reports about CFC-11 emissions in apparent violation of the Montreal Protocol. We initiated an inverse modeling study of 16 trace gases (Sulfur hexafluoride or SF6, chlorofluorocarbons or CFCs, hydrochlorofluorocarbons or HCFCs, hydrofluorocarbons or HFCs, and PFCs) to estimate U.S. national and regional GHG emissions for 2007-2018. We upgraded the NOAA flask gas chromatograph (GC), obtaining a 10-fold improvement in precision. CIRES and NOAA scientists together assessed the environmental impacts of a number of replacement compounds and potential ozone-depleting chemicals by measuring metrics for changes in climate and ozone.[117–121] The recorded laboratory data were integral to the WMO/UNEP Scientific Assessment of Ozone Depletion.

Recent studies by CIRES and NOAA scientists have also explored the connections between stratospheric variability and surface weather,[122] the impact of the stratospheric QBO on surface long-lived trace gas variability and emission estimates,[123] and how changes in the jet stream in the Southern Hemisphere can be attributed to stratospheric ozone depletion variability.[124]

Future Work of CIESRDS

CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Lead or contribute to various observations of ozone from surface to stratosphere, assuring long-term ozone climate records, guiding the rehabilitation of the ozone layer, providing the scientific basis for evaluation of the U.S. air quality in base-line conditions, and studying impacts of the anthropogenic and biomass-burning pollution on people's health in the U.S. population at large.
- Use ML techniques to explore how stratospheric ozone is changing and work toward attributing those changes to natural variability or anthropogenically-forced climate change.
- Continue to study how dynamical and radiative processes in the stratosphere impact surface conditions. Research focal points will include improvements in S2S surface weather predictions based on stratospheric conditions; improvement and extension of the Stratospheric Water and Ozone Satellite Homogenized data set for trend and variability studies; further work on the QBO influence from the stratosphere to the surface; and the development of high-altitude aircraft instruments to measure reactive nitrogen, chlorine, and bromine, allowing for detailed and precise in-situ diagnosis of radical ozone-destroying chemistry.
- Oversee weekly flask air sampling from 14 remote surface sites across the globe, measuring concentrations of ozone-depleting and climate-forcing gases in these samples using GC

instrumentation. To improve temporal granularity, automated *in-situ* GCs will provide additional measurements hourly at five remote locations across the globe.

- Collect flask measurements from aircraft, to provide regular vertical profiles of ozone-depleting and climate-forcing gasses throughout the troposphere and into the stratosphere. Results from these programs will improve our understanding of atmospheric processes such as atmospheric chemistry, tropical convection, vortex formation, stratosphere-troposphere exchange, and inter-hemispheric exchange, and will feed into NOAA's annually updated Annual Greenhouse Gas Index and Ozone Depleting Gas Index.
- Continue to monitor UTLS WV by balloon-borne FPHs at Boulder, Hilo, and Lauder. We will further expand the UTLS WV balloon-borne FPHs network to enable a more global perspective on UTLS WV changes. We will redesign the instrument to replace the HFC-23 refrigerant (used for the last 41 years) with a more environmentally-friendly coolant.
- Continue to collect, calibrate, and quality-assure ground-based climate data to guide stratospheric ozone recovery and to assess trends following the Montreal Protocol and other guidelines. Collaborate with NASA and NOAA colleagues to verify the stability of satellite operational and climate ozone records. We will develop methods to quantify how climate-related changes in the Brewer-Dobson circulation affect atmospheric composition.
- Update instrumentation systems to harness technological advances and increase program reliability. CIESRDS will expand the observing system strategically to address data gaps in important source/sink regions, particularly in the tropics, to better (1) constrain vertical and inter-latitudinal mixing, and (2) document the vertical distribution of GHG.
- Expand GHG and Earth System modeling capabilities to improve prior flux estimates and atmospheric transport models, increase optimized fluxes' spatial resolution, ingest additional data constraints, and further align research products with stakeholder needs.
- Advance research and development for GHG decision-support data sets and tools in partnership with NOAA, other agencies, academia, and public and private sectors.
- Expand research and development of innovative, reliable observational systems such as deployment on commercial aircraft and high-altitude balloons, and study the potential of other opportunities, such as rapid-response flights, increased measurement frequency, diverse collaborations, and knowledge transfer or capacity building.
- Participate in upcoming field campaigns leading the development, deployment, and data analyses of key instruments in, for example, the Asian Summer Monsoon Chemical and Climate Impact Project (ACCLIP), Atmospheric Emissions and Reactions Observed from Megacities to Marine Areas (AEROMMA), and Stratospheric Aerosol processes, Budget, and Radiative Effects (SABRE).

3.B.1.b.3 Air Quality

CIRES Background

CIRES has devoted a sustained effort in air quality research that has helped decision-makers seeking to develop effective air quality and climate policy. CIRES scientists were at the core of a team that discovered a new compound formed from oceanic emissions, leading to improved understanding of marine clouds that affect Earth's radiation budget, for example.[125] CIRES scientists led or contributed to studies that measured cleaning and personal care products—a large petrochemical source of volatile organic compounds that affect urban air quality (e.g.[126–128]); quantified oil and natural gas emissions and their air quality impacts in many U.S. locations (e.g.[129–131]); determined wintertime pollution sources;[39] measured the impacts of

wildfire emissions in the U.S. West during the FIREX-AQ study; and examined the air quality impacts of COVID-19 lockdowns.[128]

CIRES researchers have successfully developed and evaluated the representation of chemistry, emissions, and transport processes in models across fine, regional, and global scales to advance scientific understanding and improve weather, air quality, and climate forecasts. CIRES and NOAA researchers specialize in developing and evaluating state-of-the-art emission inventories used in 3D models for emission sectors including transportation[132], volatile chemical products (VCPs),[126,133] and oil and gas.[134] CIRES researchers contributed to the successful update of chemical mechanisms, such as VCP chemistry in 3D models[133] and fire chemistry in 0D box-models,[135] and significantly advanced transport in models from fine-scale processes such as planetary boundary layer schemes[136] to large-scale processes such as aerosol vertical transport via monsoons.[137]

CIRES also uses several state-of-the-art lidars to study important processes that influence dynamic atmospheric processes in the boundary layer, the troposphere, ocean ecosystems, and surface air quality. This includes an ozone differential absorption lidar (DIAL), a one-of-kind instrument that can observe ozone profiles from the surface to the upper troposphere.[138] DIAL has been used, for example, to investigate stratosphere-troposphere transport of ozone, the long-range transport of ozone from Asia, contributions of biomass burning to the regional ozone burden, and local ozone production.[138,139] Other lidar systems deployed on the ground, ships, or aircraft have enabled us to study ozone transport processes; to characterize wind flows and turbulence, including near wildfires; to evaluate the performance of numerical weather prediction (NWP) model wind forecasts; and to study ocean plankton layers. This work has revealed critical boundary layer structures important for model improvements,[140] faster development of renewable energy,[162] and the health of the atmosphere (e.g.,[142–144]). It has also been important for the mitigation of natural hazards and climate change (e.g.,[145,146]).

Future Work of CIESRDS

CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Inform model development with the use of use laboratory, field, and satellite observations including using field results to improve the representation of emissions, chemistry, and transport from fires (e.g., FIREX-AQ) and cities (e.g., Southwest Urban NOx and VOC Experiment (SUNVEx), Coastal Urban Plume Dynamics Study (CUPiDS), & AEROMMA).
- Continue chemical mechanism model development in collaboration with NOAA and the Environmental Protection Agency, working toward an operational and regulatory model that incorporates the latest science and accurate representation of multiphase chemistry.
- Expand research that improves how larger-scale weather and climate models incorporate fine-scale chemical and physical processes such as aerosol-cloud interactions.[65]
- Lead efforts to improve analysis and forecasts of wildfire smoke and emissions and impacts on air quality. Improve the Community Multiscale Air Quality (CMAQ) model to represent wildfire impacts on fine particulate matter at higher resolution than in the current operational models and include for the first time the impact on ozone pollution.
- Use NOAA Surface Radiation Budget Network (SURFRAD) measurements to evaluate satellite retrievals of clouds, radiation, and aerosols to improve satellite products. A key focus will be on developing and validating satellite and modeling tools to understand and predict air quality in an era of increasing wildfires.

- Expand NFAN sites in Ohio and Florida to better characterize aerosol characteristics and radiative properties, and design, outfit, and deploy a NOAA-funded mobile laboratory for use in field campaigns and opportunistic events. These deployments will allow us, for example, to analyze how smoke characteristics change with plume age, fire radiative power (FRP), and biomass burning fuel.
- Study impacts of stratosphere/troposphere exchange, biomass burning, and long-range transport on tropospheric ozone, with a focus on rising baseline surface ozone levels that impact the health of the U.S. population and economy. We will evaluate U.S. needs for sustained, long-term measurements to monitor tropospheric and near-surface ozone.
- Lead and participate in an intensive field campaign, AEROMMA, using aircraft observations to sample the atmosphere over urban areas in the U.S. East Coast and over the Pacific Ocean off the coast of California. The 2023 study will use new measurement capabilities to quantify changes to the atmosphere from both natural oceanic emissions[125] and from cleaning and personal care products in urban areas,[127] and will coordinate with CUPiDS to determine meteorological impacts on air quality.
- Deploy the ozone lidar to the Long Island Sound area in conjunction with the AEROMMA and CUPiDs field campaigns. These ozone lidar observations will focus on understanding the effects of the unique atmospheric dynamics at the urban-marine interface on transport and distribution of ozone downstream of New York City.
- Apply lidar-technique approaches to comprehensively study meteorological processes, vertical/ horizontal structure, and characteristics of flow systems in coastal, complex-terrain, and urban environments:
    - Design and conduct field experiments to study meteorological and atmospheric/marine boundary layer phenomena.
    - Provide engineering upgrades to mobile lidar technology including motion compensating systems, scanning capability, and data analysis algorithms.
    - Advance improvements of NWP and climate models through the evaluation of model accuracy with high-resolution lidar measurements and better understanding model ability to forecast extreme events and air-sea interaction processes.
- Continue to evaluate NOAA operational weather[147] and air-quality models and expand on this work to create a model diagnostic tool (MELODIES-MONET) in collaboration with NOAA Chemical Sciences Laboratory (CSL), NOAA Air Resources Laboratory (ARL), and National Center for Atmospheric Research (NCAR) to evaluate atmospheric composition in research, operational, and regulatory models against a variety of observations (e.g., surface, aircraft, satellite), all within a common framework.
- Continue data analysis and modeling to assess changes in emissions and urban air quality due to decreased traffic and economic activities during the COVID-19 lockdowns, using CIRES/NOAA measurements from 2020.
- Develop and improve instrumentation that defines the gold standard of atmospheric sampling, to remain at the forefront of the field. Advancements using laser-induced fluorescence, for example, will improve concentration measurements of sulfur dioxide and nitric oxide, which are important in air quality and climate.
- Contribute to the development and deployment of instrumentation of NOAA's new G550 aircraft for atmospheric sampling, to make it an effective air quality and climate research platform.

- Continue to lead key laboratory studies to determine process-level chemical measurements necessary for air quality model improvement, initially focusing on furan and phenol derivatives as well as volatile chemical product chemistry.
- Evaluate and enhance existing and upcoming satellite observations (e.g., Tropospheric Emissions: Monitoring of Pollution (TEMPO), TROPOspheric Monitoring Instrument (TROPOMI), etc) with measurements (e.g., SURFRAD), lidar observations, improved emission inventories, and modeling frameworks. For example, CIESRDS will apply observations from the ozone lidar to validate the ozone products from the geostationary satellite-borne TEMPO instrument (to be launched in December 2022).

3.B.1.b.4 Earth Radiation Budget and Climate Intervention

CIRES Background

CIRES has contributed to important modeling efforts under the Earth Radiation Budget (ERB) program. These efforts have significantly advanced the understanding of human activities that impact the Earth's radiation budget, such as marine cloud brightening, stratospheric sulfate injections, and rocket emissions of black carbon. CIRES and NOAA researchers have combined high-resolution cloud models with novel statistical emulation techniques to elucidate the local cloud responses to aerosol perturbations.[69,76,148] Key insights include the diminishing effects of aerosol-induced cloud brightening over time[68] and the optimal size distribution of seeding particles for marine cloud brightening.[149] Leveraging the strong expertise of CIRES and NOAA scientists in atmospheric dynamics and analysis of large ensemble, chemistry-climate model simulations, we have also reported on the unintended climate impacts of stratospheric sulfate injections.[150] CIRES and NOAA scientists demonstrated the potential impacts on stratospheric ozone and dynamics and provided a useful range of climate consequences from space travel by modeling clean-burning rockets[151] and stratospheric black carbon emissions from a projected increase in space traffic.[152]

CIRES scientists have been key partners with NOAA to run world-class calibration facilities and surface radiation measurement networks used to detect changes due to clouds and aerosols,[153] Antarctic UV radiation and ozone,[154] and surface conditions that control albedo (e.g., a unique long-term record of snowmelt and onset of snow dates as an indicator of a warming Arctic,). These measurements are also used to evaluate satellite retrievals, improve weather and climate models, and pursue scientific research that advances understanding of the processes driving, and being driven by, the surface radiation budget.

Future Work of CIESRDS

CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Collaborate with NOAA to expand collections of co-located measurements of cloud, surface energy budget, aerosols, surface characteristics, and boundary layer growth in new locations by participating in cross-lab and inter-agency field campaigns and new long-term sites.
- Collaborate with NOAA to develop and operationalize new boundary layer height and cloud type products at our SURFRAD stations, which will allow us to gain new insights on the relationship between surface radiation, clouds, and boundary layer growth. These combined data sets will be used, for example, to improve weather model studies for renewable energy prediction, and understanding of the connections between boundary layer growth, clouds, and surface radiation to improve weather and climate predictions.

- Improve the understanding of aerosol-cloud interactions that impact the Earth's radiation balance. This work will involve:
  - using satellite retrievals and reanalysis products to explore the spatiotemporal scales on which clouds are susceptible to brightening under different meteorological conditions.
  - incorporating multiple aerosol species within large-eddy simulations, to better interpret the implications of ship-track observations for deliberate salt-based marine cloud brightening efforts.
  - assessing "checkpoints" that need to be addressed in order for marine cloud brightening to remain a viable option within society's portfolio of climate responses, and what criteria or "exit ramps"[155] should lead to termination of such research.
- Further our understanding of the effectiveness, benefits, and risks of different sulfate climate intervention strategies with model simulations that assess impacts on atmospheric composition, dynamics, and stratosphere-troposphere coupling. In collaboration with colleagues at NCAR, we will perform further simulations to test for injection locations that are optimal for cooling efficacy.
- Elucidate aerosol-cloud-radiative forcings and feedbacks and their implications for climate change and marine cloud brightening using a state-of-the-art large eddy model and AI as a proxy model.
- Model the climate impact of novel fuel-burning rockets that are currently in development, and debris from satellite termination and re-entry vehicles, which is expected to become the largest stratospheric emission source in the coming decades.
- Contribute to the development of the Community Earth System Model/Community Aerosol and Radiation Model for Atmospheres model to simulate volcanic eruptions, which are a natural analog of aerosol-based climate intervention. Simulations will be constrained with observations and reanalysis data and will investigate the formation of sulfate aerosols from gaseous precursors, effects on stratospheric WV and ozone, and optical properties of sulfate aerosol.
- Enhance ozone and WV sampling through the troposphere and stratosphere to study the impacts of changes in these greenhouse gases on surface temperatures, atmospheric transport, and precipitation. These data will provide a valuable contribution to the development of the air-quality forecast models.
- Make stratospheric measurements using newly-developed gas and aerosol instrumentation, and improve modeling and forecasting capabilities to address knowledge gaps in understanding Earth's radiation budget and changes in the stratospheric baseline when evaluating future potential climate interventions
- Continue laboratory experiments related to climate intervention using NOAA's diffuse reflectance infrared Fourier transform spectroscopy. Initial studies will target absorption coefficients of calcium minerals that are being discussed as potential climate intervention materials.
- Conduct high-quality surface radiation measurements, extending records to increase their value for better discrimination of climate trends and variability. These data are critical for the prediction of climate and weather.

3.B.2. Climate Science and Prediction

3.B.2.a. Overview

Climate system variability and change is driven by local-to-global processes. CIESRDS in partnership with NOAA collaborators will address the drivers of climate variability and extremes, to provide better climate predictions across various time and spatial scales. CIRES scientists have an outstanding record of pursuing world-class research to advance our ability to understand and predict the climate system, and CIESRDS will continue this endeavor to address the key challenges of the next decade. Proposed CIESRDS work in this theme will include robust observational techniques, participation in key field research events, and novel data analysis approaches. Further, we will advance the field by developing new analytical and modeling tools to best understand and predict the components of the Earth System and their teleconnections. The results will lead to supporting NOAA science capabilities and applications. CIESRDS will draw from the expertise of CIRES scientists to increase the ability to predict changes and extremes in the climate system across temporal and spatial scales. We will apply new tools, such as AI/ML and UxS to several of the specific topics described below in more detail. Much of this work will be performed by CIESRDS experts. The goal of this work is "*to accelerate the transition of climate science research advancements to enhance NOAA mission capabilities.*"

Below, we describe potential work in four relevant topical areas associated with climate science and prediction: (1) Boundary Layer Observations and Processes, (2) Predictability of Extremes, (3) Attribution Research, and (4) Tropical-Extratropical Interactions. It should be noted that some projects described in other themes—especially Regional Science and Applications, Weather Research and Forecasting, and Ecosystems (3.B.4)—also meet the Climate Science and Prediction research needs of NOAA.

3.B.2.b. CIESRDS Proposed Work for 2022-2027 and Beyond

3.B.2.b.1 Boundary Layer Observations and Processes

CIRES Background

CIRES scientists and engineers have developed and deployed innovative measurement techniques and observational platforms,[156–160] and applied state-of-the-art data processing methods to derive more accurate meteorological variables.[161] We've used these problem-focused observations (a) to improve understanding of key physical processes,[158,162,163] (b) for model verification[164,165] and to identify weaknesses in models,[166] and (c) to contribute to the improvement of model parameterizations so that these improvements can be transitioned to the

operational models.[167] The data collected are also made available to the scientific community (e.g.,[168–171]). This work represents a research-to-operations-to-research (R2O2R) effort with the ultimate goal of helping NOAA diagnose and correct systematic errors in key operational models, saving lives and property.

Future Work of CIESRDS

CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Deploy established and new observing systems, analyze observed and derived meteorological variables and use the observations for atmospheric process understanding and for model evaluation. The collected observations will be used to diagnose the systematic errors in NOAA NWP models such as the Rapid Refresh (RAP) and the HRRR, as well as the Global Forecast System (GFS), and the Finite-Volume Cubed-Sphere (FV3).
- Collect observations and/or analyze data from many field campaigns, often with partners in DOE, other universities, and private institutions, and with all of the NOAA Earth System Research Laboratories.
    - MOSAiC, a year-long international, multi-institutional study to understand physical, chemical, and biological processes contributing to Arctic climate response to rapidly changing global conditions. The field phase concluded in 2020; analysis and modeling efforts will continue for many years. CIESRDS will focus on physical aspects of air-sea exchange of climate-active gasses in the sea ice environment.
    - SAIL/SPLASH (Surface Atmosphere Integrated Field Laboratory/Study of Precipitation, the Lower Atmosphere, and Surface for Hydrometeorology), held in Colorado September 2021-June 2023, aimed at advancing atmosphere-through-bedrock understanding of mountainous water cycles by collocating atmospheric observations and surface and subsurface hydrologic observations. These observations will be used to identify model errors that are usually difficult to isolate in complex terrain, with usually limited atmospheric and land-surface observations.
    - VORTEX-SE (Verification of the Origins of Rotation in Tornadoes EXperiment-Southeast), was held in Alabama in 2016-2018 and was part of a long-term, ongoing effort to understand how environmental factors characteristic of the U.S. Southeast affect the formation, intensity, structure, and path of tornadoes (the first Vortex campaign started in 1994). CIRES deployed wind and precipitation radars as part of the latest project, and CIESRDS will continue with the data analysis and model development/evaluation as part of this and future studies.
    - WFIP3 (third Wind Forecast Improvement Project), a comprehensive observational and modeling study of the coupled atmospheric and oceanic boundary layers, will dramatically improve offshore wind resource measurement and modeling science. This mission is planned for 2023 in the U.S. Northeast. CIESRDS will have substantial leadership and involvement in this upcoming project.
    - ATOMIC, a six-week campaign in the Northwest Tropical Atlantic in 2020 that provided an array of oceanic and atmospheric observations to investigate cloud and air-sea interaction to advance U.S. weather and climate predictions. With the campaign measurements, CIESRDS will develop a bias-corrected set of observations to evaluate weather and climate models, assess reanalysis data, and calibrate and validate satellite-derived retrievals and gridded satellite data products.

3.B.2.b.2 Predictability of Extremes, Trends, and Climate Variability

CIRES Background

Extreme climate, water, and weather events such as heatwaves, cold spells, droughts, and floods can profoundly affect society and the environment, resulting in loss of life, property, and natural habitat. Past CIRES work in this area has focused on (1) Developing and releasing unique long-term global atmospheric and oceanic reanalysis datasets to better characterize the changing statistics of weather and climate extremes over the past 210 years and to provide verification datasets for model simulations;[172,173] (2) Developing and using new and improved parametric representations of the probability distributions of weather and climate anomalies to better understand and provide more statistically robust estimates of the changing statistics of extremes in both models and reality;[174,175] (3) Designing and performing large ensembles of empirical and numerical model integrations with and without candidate precursors and forcings to quantify their role in the generation, maintenance, and decay of extreme events, both in general and in specific instances, such as along the U.S. Coasts;[176] and (4) Developing and testing stochastic parameterizations of chaotic physical processes in weather and climate forecast models, with particular emphasis on how they impact the probability distributions and extremes of weather[177] and climate anomalies.

CIRES scientists have focused much research specifically on hydrometeorological extreme events, such as floods and drought, flash floods, and flash droughts. We are world leaders in understanding the role of the interactions between the atmosphere and land surface that are central to extremes and their use in early warning, drought monitoring, analysis, predictability, and forecasting. For example, CIRES scientists have developed two significant drought monitoring products: the Evaporative Demand Drought Index (EDDI)[178] and an index that uses soil moisture percentiles from the National Water Model (NWM). CIRES scientists conducted the first national variability analysis of evaporative demand, and we are moving to expand this technique to cover the net difference between supply and demand in drought.

Future Work of CIESRDS

CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Develop and use a combination of theory, observations, long-term reanalysis datasets, and model simulations and predictions to improve our understanding and predictability of extremes on time scales of days to decades.
- Examine to what extent the gap between current and potential prediction skill of extreme anomalies can be reduced by improving forecast initial conditions, model resolution and physics, and stochastic parameterizations of chaotic physical processes.
- Investigate whether there are untapped sources of predictability in the climate system beyond the roughly two-week predictability limit of daily weather, associated with the predictability of sea-surface temperature (SST) anomalies (El Niño-Southern Oscillation (ENSO)-related and unrelated), subsurface ocean variations, stratospheric sudden warmings, and land-surface anomalies.
- Explore ways to use the enhanced understanding and predictability of changing extreme risks to inform socio-economic risk management of floods and droughts, heat waves, hurricanes, disruptions in energy supply, marine resources, and national security.

- Evaluate trends on interannual-to-decadal timescales to establish context for changes in S2S prediction skill. This will include the application of NOAA models to improve understanding of the attribution and predictability of extreme or unusual climate/weather events (such as droughts) at S2S time scales.
- Collect, analyze, and compare climate simulations from other climate modeling centers (e.g. NCAR, Geophysical Fluid Dynamics Laboratory (GFDL), Canadian Climate Center). For example, we will perform a process-oriented hydrological evaluation of Climate Model Intercomparison Project (CMIP6) climate models, e.g. investigating the role of spatial resolution on the water/energy budget in these models, and the role of precipitation variability on runoff generation.
- Identify sources of predictability for processes, such as soil moisture, ocean heat content and ocean-atmosphere coupling, stratosphere-troposphere coupling, and land-atmosphere coupling, at S2S timescales.
- Improve NOAA's prediction capability at S2S timescales. We will focus on predictions of key quantities such as precipitation forecasts in the U.S. West; hurricane activity in the Atlantic Basin; fire weather and fire conditions; hydro-climate; etc. This will include supporting operational week 3-4 forecasting.
- Continue collaborating with the NOAA Environmental Modeling Center (EMC) to improve NOAA's Unified Forecast System (UFS) of FV3/ Modular Ocean Model (MOM6)/The Los Alamos Sea Ice Model (CICE5) coupled model. We will focus on reducing model biases by (1) introducing fractional landmass in the FV3 atmospheric grid and (2) using advanced model physics. The improved FV3/MOM6/CICE5 coupled model is expected to be more skillful for the UFS.
- Identify sources of bias presenting at S2S timescales in NOAA forecast models. For example, characterizing and understanding stratospheric biases in models (both forecast and coupled climate models), and how such biases influence predictability or tropospheric variability.
- Use expertise in cloud microphysical and mesoscale modeling and in model sensitivity analysis to improve our understanding of physical processes related to orographic precipitation and to identify potential shortcomings in quantitative precipitation forecast (QPF) produced by NOAA operational models. In the SPLASH project domain, for example, this will involve traditional and novel observation techniques, characterization of relationships from observations and process understanding, and advanced modeling to investigate climate system variability, trend analysis, extremes, and dynamics.
- Investigate the regional meteorology in Colorado’s East River Basin with a focus on precipitation processes and seasonal variability, using a 36-year model dataset. The project focus is on the large-scale patterns associated with extreme precipitation events and comparing those patterns with the typical large-scale patterns over this region. This will better specify the effects of climate variability and change on the water cycle and the occurrence of extreme events and their impacts.
- Evaluate operational and experimental forecasts and model simulations as appropriate in terms of QPF, temperature, and other variables for selected case studies using observations collected during the SPLASH campaign. We will evaluate experiments testing different "complex" microphysics schemes available in the UFS for the understanding of mixed-phase processes over the East River Basin, which may help with understanding the microphysical processes represented in the UFS and if improvements can be made.

3.B.2.b.3 Attribution Research

CIRES Background
CIRES has extensive expertise in the identification and quantification of physical processes that produce variability, change, and extreme events in the climate system. Here we call that attribution research. For example, NOAA and CIRES partners have led attribution studies that focused on unexplained features of observed extreme daily precipitation trends over the contiguous United States (CONUS),[179,180] the different seasonal climate impacts of tropical Pacific SST warming patterns on the United States,[181] U.S. weather forecast model skill,[182] and evaluation of extremes in temperature (e.g., heat waves) and precipitation (e.g., U.S. West droughts and floods).[179,180,183]

Future Work of CIESRDS
CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Develop event attribution methods for temperature, drought, and precipitation extremes. Some examples of this work include the identification of causes of droughts in the U.S. West by analysis of observed data and hydrologic, climate, and atmospheric models. We will work to identify trends in precipitation and drought to determine the role of multidecadal variability in sea-surface temperatures and other boundary forcings, and the extent to which causal factors are anthropogenic.
- Apply AI/ML, empirical orthogonal functions, and statistical methods to elucidate drivers of climate variability. For example, we will apply these tools to the analysis of large ensembles of climate model simulations to distill covariance information from interannual to interdecadal time scales.
- Evaluate “what if” scenarios by performing climate simulations with various configurations of forcings, e.g., “factual” and various “counterfactual” Atmospheric Model Intercomparison Project-type simulations. We will perform multidecadal projections using empirically constrained climate models based on plausible future scenarios for adaptation planning purposes.
- Develop a complete attribution of trends and variability in evaporative demand across the globe, building off research uncovering the drivers of variability in evaporative demand across CONUS.
- Support the transfer of research methods described here and elsewhere to NOAA partners including the NOAA EMC, Climate Prediction Center (CPC), and Storm Prediction Center, to help create or enhance critical operational forecast products.

3.B.2.b.4 Tropical-Extratropical Interactions

CIRES Background
CIRES has extensive expertise in developing an improved mechanistic understanding of the interactions among different components of the coupled atmosphere-ocean-land system. This expertise has particularly been applied in the context of interactions between the tropics and extratropics and between convection and dynamics internal to the tropics, with the ultimate goal of improving NOAA's operational prediction capabilities. CIRES has developed various research tools to enable these efforts, ranging from incisive process-level diagnostics[184–186] to cutting-edge empirical-dynamical, model-analog, ML, and numerical models.[145,187–191]

Currently, CIRES scientists in collaboration with NOAA colleagues are investigating global model convection parameterizations and how their formulation impacts tropical simulation fidelity;[191–193] developing empirical-dynamical models able to identify when, and diagnose why, extratropical sub-seasonal forecasts will be skillful;[145,187] investigating climate models to outline how Pacific internal variability and future changes in ENSO and land-surface memory will combine to modulate North American drought risk;[194,195] and developing empirical-dynamical models that leverage tropical-extratropical SST and sea-surface height (SSH) anomalies to provide coastal ocean forecast outlooks relevant to marine resource managers.[196,197] CIRES and NOAA partners have also looked at how the basic state affects tropical-extratropical interactions (in both directions), with an emphasis on the Madden-Julian Oscillation (MJO) and moist Kelvin waves.[198,199] More broadly, CIRES has leveraged the nudging capability of the UFS in collaboration with NOAA and other partners to quantify the impact of tropical forecast errors on extratropical prediction skill of precipitation over the western United States at Weeks 3-4, via Rossby wave teleconnections.[200,201] We are also studying the impact of tropical forecast skill on Northern Hemisphere forecasting skill, and working on the development of methods to model moisture-convection coupling.

Future Work of CIESRDS

CIESRDS scientists, in collaboration with NOAA partners, will:

- Further develop ML techniques pioneered at CIRES/Physical Sciences Laboratory (PSL), including linear inverse models (LIMs) and model-analogs, along with the development of other new ML approaches with a specific focus on diagnosis of system dynamics of climate variability, on both S2S and seasonal-to-decadal (S2D) time scales.
- Diagnose and study the predictability of ENSO, including its diversity and global teleconnections to atmosphere, land, and ocean; in nature and within climate models; using LIMs and other ML approaches that diagnose system dynamics; on synoptic through multi-year/decadal time scales; in current and future climates.
- Advance UFS nudging capability, including the development of hybrid UFS-LIM formulations using dynamical mode-based filters allowing for the isolation of model errors and biases that are specifically relevant to skillful sub-seasonal forecasting. Specific goals include: (1) establishing an upper bound on the downstream CONUS forecast skill that might be realized if tropical modes of variability (e.g., the MJO, ENSO, and QBO) were perfectly simulated in the UFS, and (2) quantifying how the inaccurate simulation of these dynamical modes by the current generation UFS causes errors and biases that degrade CONUS forecast skill.
- Improve sub-seasonal forecast skill over the CONUS and along the North American coasts by diagnosing and studying Earth system predictability on S2S time scales. We will accomplish this by developing LIMs and other ML approaches that diagnose system dynamics to examine the interaction of tropical modes of variability (ENSO and the MJO) with the QBO, and their interaction with the extratropics including worldwide teleconnections.
- Improve hydroclimate/fire weather/flash drought S2S/S2D prediction and diagnosis of predictability. We will target relevant variables including soil moisture and precipitation, in regions such as CONUS, SW Asia, East Africa, and the Greenland ice sheet.
- Improve model diagnostics by developing new process-based diagnostics used to verify UFS and other models.

- Improve understanding of subtropical air-sea interaction processes and their effects on the climate system. We will use data collected during ATOMIC and a Large Eddy Simulation model to investigate mesoscale air-sea interactions.

3.B.3. Earth System Data Science, Stewardship, and Application

3.B.3.a. Overview

CIRES has been managing NOAA Earth system data for more than 50 years, using state-of-the-art technologies to make data findable, accessible, interoperable, and reusable (FAIR); and building derived products. CIESRDS will continue this work, to help meet the Nation's evolving needs. We have significant expertise in building and enhancing software and data ingest pipelines that manage and bring data into NOAA's archive at National Centers for Environmental Information (NCEI), and have ensured compliance with NOAA data management policies and practices (NOAA Administrative Order 212-15). We have collaborated widely to skillfully collect, organize, distribute, and analyze datasets from the surface of the Sun to the bottom of the ocean, including geophysical data, coastal bathymetry, tsunami and hazards data, precise geodetic measurements, paleoclimate data, biological data, and world-wide geomagnetic, solar and ionospheric measurements. We work to ensure that NOAA and other Earth system data are easily accessible by a diversity of users including emergency managers, satellite operators, weather and climate scientists, the fishing industry, coastal planners, and many others. Our partners include the World Glacier Monitoring Service, the U.S. National Ice Service, NOAA National Data Buoy Center, NOAA National Tsunami Warning Center, NOAA Pacific Tsunami Warning Center, and the NOAA Center for Operational Oceanographic Products and Services.

Below, we describe our accomplishments and proposed CIESRDS projects, organized into three categories: Properly Managed Data, Data Science and Research, and Modern Data Access Systems.

3.B.3.b. CIESRDS Proposed Work for 2022-2027 and Beyond

3.B.3.b.1 Properly Managed Data

CIRES Background

The discovery, access, archival, and use of well-managed and well-described Earth system data are integral to an improved understanding of Earth's natural processes, and enabling resilience in the face of change. CIRES scientists have an excellent record of using state-of-the-art technology to develop and maintain key environmental datasets for NOAA, developing, calibrating,

processing, and archiving data collected by satellite, ship, and autonomous unmanned platforms. For example, using the latest in NoSQL database technologies, CIRES staff developed and supported the transition into operations an enterprise data discovery catalog, NOAA OneStop, that holds over 80,000 dataset collections and more than 24 million unique files.

Serving NOAA's needs in coastal and marine geophysics, CIRES staff have led NCEI's development and management of big data related to coasts and oceans. This includes historical event, image, and tsunami deposit databases; water-level and tide gauge data; trackline geophysical data, including geomagnetic data; and hull-mounted sonar, passive acoustics, and crowdsourced bathymetry (CSB). Collectively, these data are critical for understanding and mitigating natural hazard risk, supporting navigation, assessing fisheries habitats, and establishing U.S. sovereign rights. Among our accomplishments in this area, CIRES has improved the ingest, processing, quality assessment, visualization, and public access to NCEI's trackline and multibeam bathymetry data, as well as historical hazard events and water-level data, using modern technologies, including the cloud.[202–205] CIRES has also been instrumental in establishing new NCEI-based big data archives in water-column sonar, passive acoustics, and CSB.[206–208] CIRES developed CruisePack, an easy data packaging tool that increases the flow and quality of a wide variety of ship-collected NOAA geophysical data to NCEI.[209,210]

NCEI, which is responsible for the stewardship of the NOAA environmental data, and CIRES calibrates, validates, processes, and archives these data for a number of satellites including the GOES series, the Deep Space Climate Observatory (DSCOVR), and the future Space Weather Follow-On (SWFO) satellite. This information supports severe space weather forecasts that aid in the protection of satellites and ground-based systems as well as space weather, atmospheric, and solar research (See, for example, Space Weather Research and Prediction, Section 3.B.6). For example, CIRES has successfully provided real-time thermospheric and ionospheric products from the Global-scale Observations of the Limb and Disk (GOLD) satellite,[211] an improved long-term ultraviolet dataset (e.g.,[212]), and solar coronal studies.[213] CIRES has also developed reprocessing scripts to provide science-quality GOES-R and DSCOVR datasets to NOAA and the community.

CIRES staff have managed a diversity of paleoclimate and cryospheric data that inform our understanding of Earth's past and future climates, and enable safe navigation in rapidly changing regions such as the Arctic. Because instrumental records of climate are rarely more than one century long, data from paleoclimatic proxies spanning hundreds to millions of years provide a unique way to understand the full range of climate variability and change. CIRES has stewarded a wide diversity of paleoclimatic data in the World Data Service for Paleoclimatology (WDS-Paleo) repository at NCEI, which provides a critical capability for this research by accepting diverse datasets from individual researchers and standardizing, preserving, and distributing them.[214] CIRES-managed datasets within WDS-Paleo include the International Tree-Ring Data Bank (ITRDB), the world's largest public archive of tree ring data from more than 5,000 sites on six continents, which helps researchers put recent climate conditions into historical perspective; and the International Multiproxy Paleofire Database (IMPD), an archive of fire history data derived from natural proxies, such as tree scars, charcoal, and sediment records. The NOAA-supported team at CIRES' National Snow and Ice Data Center (NSIDC) has long managed, archived, and published cryospheric data sets in collaboration with NOAA, with

an emphasis on in-situ data and data from operational communities, such as the U.S. Navy. NOAA@NSIDC datasets have included sea ice motion, concentration, and extent from various sources; Great Lake daily ice observations; and World Glacier Inventory data. Our work has enabled the use of these datasets by a wide community of researchers.

Future work of CIESRDS
CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Expand historical hazard-event databases, including the tsunami deposit and natural hazards imagery databases, to support coastal communities.
- Distribute, archive, and steward digital water-level data, including Deep Ocean Assessment and Reporting of Tsunami data and coastal tide gauge data, and work with international partners to expand tsunami-related water-level data availability.
- Enhance and expand NCEI's marine geophysical and ocean acoustics data pipelines, build products and tools to quality assess, visualize, and disseminate these data, and engage with stakeholders to gather and archive additional NOAA, national, and international marine geophysical data.
- Steward total solar irradiance measurements from instruments such as the Total Irradiance Monitor and atmospheric/ionospheric profiles derived from the Global Positioning System and other satellite systems (e.g., Constellation Observing System for Meteorology, Ionosphere, and Climate-2 (COSMIC-2).
- Distribute, archive, and steward space weather data and products from the Space Weather Science Center, including, to start, data from the deep space SWFO-L1 mission.
- Expand and enhance WDS-Paleo datasets, such as the ITRDB and IMPD, to ensure findability, accessibility, interoperability, and reusability.
- Develop products from the WDS-Paleo archive that serve a broad range of users and contain long-term value for national and international initiatives and assessments.
- Conduct code refactoring on critical sea ice and other cryospheric products, to reduce complexity and improve maintainability.
- Update daily Multisensor Analyzed Sea Ice Extent - Advanced Microwave Scanning Radiometer 2 (MASIE-AMSR2) high-resolution sea-ice concentration data to incorporate improved AMSR2 fields, supporting improved ice forecast model development.
- Reformat the Daily Snow Data Assimilation System data to NetCDF, pushing them to NOAA PolarWatch.
- Upgrade the interface to the Glacier Photograph Collection.

3.B.3.b.2 Data Use and Science

CIRES Background
Exploiting the NOAA environmental data at NCEI that CIRES manages, we have had exceptional success in data science and research activities in support of NOAA's mission. This success derives from our deep expertise and experience in basic and applied geomagnetism, and integrating bathymetry and topography at the coastline.

Through the years, CIRES has developed and released several world-standard global geomagnetic field models and products. This included the WMM,[21,215–217] which is the standard model used by the U.S. government for navigation, attitude, and heading referencing systems using the geomagnetic field. CIRES also developed NOAA's High Definition Geomagnetic

Model (HDGM),[218] the Earth Magnetic Anomaly Grid at 2 arc-min resolution (EMAG2v3),[219] and the International Geomagnetic Reference Field.[220–223] CIRES provided magnetic satellite mission advisory support to NOAA and the National Geospatial-Intelligence Agency (NGA), including exploring the feasibility of producing future WMMs from alternative data sources,[224] and developed NOAA's CrowdMag, a citizen science mobile app collecting geomagnetic data from tens of thousands of smartphones around the world. CIRES also developed an ML model to predict the geomagnetic Disturbance-storm-time (Dst) index from solar wind measurements and helped NOAA conduct an open competition to improve this model.

CIRES scientists have explored the extensive collection of bathymetric data at NCEI to develop a suite of integrated bathymetric-topographic coastal DEMs of U.S. coasts, as well as the popular ETOPO1 global relief model,[225] in support of NOAA's storm surge and tsunami modeling efforts. These DEMs are used by NOAA, the National Tsunami Hazard Mitigation Program (NTHMP), and State partners to forecast and hindcast coastal flooding. CIRES DEM research included modeling of vertical uncertainty in DEMs[226] and the impact of that uncertainty on coastal flooding.[227,228] Identifying U.S. coastal communities and offshore waters with large DEM uncertainty aids in prioritizing future topographic and hydrographic surveys, thereby improving the fidelity of coastal process modeling.

Using the CIRES-established passive acoustic data archive at NCEI, CIRES led research to explore marine soundscapes using datasets collected across three separate monitoring efforts to demonstrate the value of centralized and cloud-based access to these data.[229] CIRES participated in research to extract humpback whale songs from a large dataset collected across the Pacific over 14 years using ML.[230] CIRES also led research with the CU Department of Computer Science and NOAA Fisheries to identify fish from decades of archived sonar data using ML.[231]

Separately, CIRES played a significant, leading role in producing the 1500-page scientific and technical documentation supporting the continental shelf limits of the United States, which will be released in 2022.[22] This U.S. Government document will establish—consistent with international law—the full extent of the U.S. continental shelf, which will add nearly one million square kilometers of the seafloor to which the United States will have sovereign rights to utilize or conserve.

For NOAA's GOES-R space weather satellite data at NCEI, CIRES has developed 34 space weather products (e.g.,[232–234]). These products are used operationally by NWS/Space Weather Prediction Center (SWPC) space weather forecasters to provide warnings about potential impacts, such as radio blackouts, satellite electronics upsets, and radiation risks for astronauts (Section 3.B.6).

The CIRES team at the NSIDC has been providing trusted data management and research-relevant products to NOAA, as well as other federal agencies, for decades. Sea ice information, for example, has supported critical research like that behind a National Marine Fisheries Service proposed rule change[235] for ringed seals, which cites NSIDC's Sea Ice Index. Other NSIDC data are also foundational to the Climate.gov Dashboard and NOAA's annual Arctic Report Card.[236] NSIDC's work has also made historical archival materials, such as

mid-19th Century glacier photographs, available for research; the work has helped scientists interpret long-term snow and ice trends and has won the International Data Rescue Award.[237]

Future work of CIESRDS

CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Leverage our research capabilities to continuously improve NOAA's geomagnetic models and products. In particular, we will use ML to improve geomagnetic forecasts and the calibration of smartphone magnetometers.
- Support NOAA, NGA, and the wider community using the WMM. This includes monitoring the performance of WMM2020; producing, releasing, and supporting the WMM2025; producing a WMM error model; and developing a strategy for WMM2030 creation.
- Provide magnetic satellite mission advisory support to NOAA and NGA, including investigating the requirements of a U.S. magnetic satellite program to support the WMM.
- Investigate the use of geomagnetic data and products in support of Alternative Positioning and Navigation in situations where access to GNSSs is unavailable.
- Continue developing, releasing, validating, and supporting annual updates of NOAA's HDGM based on the most recent satellite data available and available new survey data.
- Update existing coastal DEMs and expand coverage of NCEI's tiled framework as prioritized by NWS and the NTHMP, and include the U.S. West Coast and Alaska as new bathymetric and topographic data are made available.
- Develop the ETOPO 2022 global relief model at an enhanced 15 arc-second resolution, incorporating recent advances in data sources and processing techniques.
- Work with international partners to develop additional, advanced water-level data products, including enhanced spatial metadata (source data lineage) and uncertainty products.
- Develop enhanced processing algorithms to refine tsunami detection.
- Exploit NOAA space weather data for scientific research into space weather forecasting, solar dynamics, the geospace environment, and terrestrial ground and atmospheric impacts of space weather. (Also see Section 3.B.6)
- Lead a pilot project to develop a community-focused, national cyberinfrastructure capability for passive acoustic monitoring data, technology, and best practices to promote improved, scalable and sustainable accessibility and applications for management and science.
- Expand current research applying AI to decades of archived water column sonar data. CIESRDS scientists will also develop ways to integrate marine environmental data to better monitor ocean change.
- Conduct research within cloud-based environments to enable new science through ML, data visualization and exploration, and Big Data analytics. We will develop algorithms to investigate Earth system data, including creating and sharing training datasets.
- Ensure the continuity of cryospheric products with version updates, to enable the continued research and other use of data, including advanced microwave data to support ice forecasts. We will sustain the Sea Ice Index through the anticipated end of passive microwave instruments now in use.

3.B.3.b.3 Modern Data Access Systems

CIRES Background

Modern data access systems allow for enhanced usability, accessibility, and integration of NOAA environmental data for scientific research and decision-making. In today's era, this means getting such data into the cloud, where they can be accessed, integrated, and used by AI and ML algorithms. NCEI's current on-premise enterprise archive and access software systems utilize an architecture that supports horizontal scaling by NCEI software systems, a requirement needed to support high volume throughput from NOAA's diverse observing system platforms. Implementing scalable systems in the cloud will allow scientists to perform large-scale big data analytics that simply aren't possible with on-premise software solutions.

Over the past five years, CIRES has built and enhanced modern data access and enterprise software systems for NCEI and NESDIS, especially in the cloud. This included developing an enterprise data ingest capability that was transitioned to operations at NCEI's Asheville and Boulder locations. CIRES conducted research and provided development support that resulted in an operational NESDIS Common Cloud Framework (NCCF), and spearheaded several software development activities that rely on Amazon Web Services (AWS) and database technologies as part of the ongoing NESDIS Cloud Archive Project (NCAP).

CIRES facilitated cloud access to the water-column sonar, passive acoustics, and CSB archives,[207,238] and developed a new cloud application called EchoFish to visualize and explore these data in an interactive way, and a prototype data delivery system with a map interface for the CSB data.

On the modern Geographic Information Systems (GIS) front, CIRES has contributed to improved data discovery, data access, and visualization of archived datasets by maintaining and improving NCEI's suite of geospatial web services and map viewers, covering a wide array of data types, such as NCEI's multibeam bathymetry mosaic. CIRES also helped improve geospatial services to provide access and visualization for NOAA Ocean Exploration data, such as the NOAA Ship *Okeanos Explorer* Live Operations Map, Remotely Operated Vehicle (ROV) dive tracks, and associated bathymetric products. Many of these modern GIS services utilize capabilities in the NOAA GeoPlatform (NOAA's instance of ESRI's ArcGIS Online), for improved performance, reusability, and flexibility.

Future Work of CIESRDS

CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Use the latest advances in GIS, NewSQL database management systems, and cloud-based data access and distribution systems to meet the needs of NOAA and the scientific community related to the discovery, use, and preservation of NCEI's environmental data.
- Modernize geospatial web services and interactive mapping applications (map viewers), using cloud-based technology where possible (NOAA's GeoPlatform/ArcGIS Online), to improve the discovery, access, and visualization of NCEI's environmental data.
- Using agile principles, produce innovative cloud-based workflow systems that improve the management, documentation, display, discovery, use, and preservation of NOAA's geophysical and environmental data sets (e.g., gridded satellite products, in situ measurements, and acoustic data).

- Improve NOAA's enterprise software systems and architecture that enable cloud-based data management, data access, and archival to ensure that NOAA's stewarded data are preserved, well documented, accessible, and useful for researchers and the public far into the future. This work includes a transition to cloud-based systems where scientists employ next-generation research techniques that rely on workflow automation, big data, and AI.
- Collaborate with NOAA's National Centers for Artificial Intelligence to transform NCEI environmental datasets into cloud-native formats and standards that enable their use in AI/ML algorithms.

3.B.4. Regional Science and Applications

3.B.4.a. Overview

CIRES has always had a strong focus on climate and weather science. Because the impacts of climate variability and change are felt so strongly at regional scales, CIRES has developed unique experience in regional science and applications. Our past work aligned with this theme includes, for example, enhanced measurement, analysis, and understanding of coupled processes that modulate extreme events on all scales and advanced observation and assessment of how changes in regions (e.g., tropics and poles) impact the global climate system. We have transitioned research activities to operations through testbeds (e.g.the Developmental Testbed Center serves to transition new weather model techniques, tools, and components from the modeling community to the NWS; the Hazardous Weather Testbed provides a structured experiment for NWS forecasters to test and evaluate new applications developed by researchers); and we have worked to rapidly identify the various contributors to extreme events (e.g.,[239]). CIRES scientists have developed decision-support tools (e.g., a new Hazard Services architecture and applications for the NWS forecasters to expedite watches, warnings, and advisories to the public); and we have developed and implemented innovative data assimilation methods for models (e.g., HRRR uses 3km ensemble data assimilation for improved storm prediction for 1-12 hours) and worked in model verification (e.g., Model Evaluation Tools (MET) METexpress)

CIRES hosts two centers of excellence in the production of usable science[240] and applications serving society's needs at the regional scale, including water management decision making, community adaptation, state wildlife and drought planning, and the land-management needs of communities, states, regions, and Tribes: The WWA and the North Central Climate Adaptation Science Center (NCCASC) (Institutional Capabilities and Composition, Section 3.C.).

CIRES has applied our research and development expertise to terrestrial and oceanic systems and to understanding and forecasting heat and cold waves, floods, wildfires including smoke

modeling, droughts, and more—much of this work is now incorporated into operations and decision-support systems, e.g. HRRR-Smoke (described in more detail in Theme 7: Weather Research and Forecasting). In our regional work, we have collaborated widely, including with the National Integrated Drought Information System (NIDIS), where most staff are CIRES; with our own Western Water Assessment (WWA); through the Atmospheric Science for Renewable Energy program; and in NOAA testbeds that include the Hydrometeorology Testbed and the Hazardous Weather Testbed.

CIESRDS will continue this impactful work to pursue research that addresses regional science and applications. Potential future CIESRDS projects below are divided into three categories: Hydrometeorology, NIDIS, and Polar Processes. Other research that directly addresses the needs outlined in this research theme are presented in Climate Science and Prediction (Section 3.B.2) and Weather Research and Forecasting (Section 3.B.7).

3.B.4.b CIESRDS Proposed Work for 2022-2027 and Beyond

3.B.4.b.1 Hydrometeorology

CIRES Background

CIRES scientists have worked with NOAA and other scientists to improve predictions of precipitation and streamflow through better observations and increased knowledge of hydrometeorological phenomena. We make observations and use them to enhance NOAA's existing operational data and to provide new insight into precipitation processes, and we use observations and models to improve process understanding across the hydroclimatic spectrum—particularly at the extremes of floods and droughts. An important element of this work is that we then apply this new science by engaging with NOAA's stakeholders to co-develop decision support tools for forecasting, early warning, and monitoring. For example, California decision-makers can readily access timely Advanced Quantitative Precipitation Information (AQPI) information,[241] CIRES experts in NIDIS are working with drought stakeholders to provide simulations in support of drought monitoring in the United States[242] and internationally,[243] and other CIRES scientists are working to expand the utility of our drought-monitoring products to the fire-weather prediction community.[244]

Recent breakthrough work by CIRES and NOAA partners has focused on drought, precipitation extremes, soil moisture prediction, and fieldwork. We overturned the temperature-proxy paradigm in the estimation of evaporative demand (E_o; the thirst of the atmosphere) and improved national and global drought-monitoring by developing a new E_o-based drought metric.[245] We operationalized this metric at the NOAA National Water Center (NWC),[178,246] and we are at the forefront of the emerging field of "flash" drought analysis and prediction.[247–250]

CIRES and NOAA scientists have world-class expertise in analyzing precipitation extremes, both estimated (Qualitative Precipitation Estimate (QPE)) and forecasts (QPF). We significantly advanced the understanding of the drivers of extreme precipitation events in mountainous regions,[251–254] assessed multiple aspects of high-resolution QPE in California,[254,255] developed a method to account for large QPE uncertainty when validating precipitation forecasts,[256] and evaluated QPE skill using simulated satellite radiances. We have assessed high-resolution forcings for the NWM using both deterministic and ensemble versions of the HRRR model.[257] We evaluated NWM forecasts for operational reservoir management,[258] and investigated the

NWM's representation of hydrometeorological extremes, including retrospective analysis for drought-monitoring applications and forecasts of a catastrophic flood event.[257] CIRES and NOAA collaborators completed the development of the AQPI System, which integrates X-band and C-band radars deployed as part of specific projects, local observations, HRRR, NWM, and USGS's Coastal Storm Modeling System (CoSMoS) (e.g.,[256,259,260]).

CIRES has extensive fieldwork expertise, most recently, in NOAA field programs that have involved building, deploying, and acquiring data from in-situ and remote sensing instruments to observe WV, clouds, and precipitation and better understand precipitation processes. In work on atmospheric river events,[261–264] we have identified dynamic and thermodynamic conditions resulting in prolonged precipitation events causing significant societal impacts. The El Niño Rapid Response (ENRR) campaign[265,266] included CIRES scientists making in-situ observations from weather balloons and dropsondes deployed from crewed and **uncrewed aircraft**, to examine the connection between tropical dynamics with mid-latitude precipitation. CIRES scientists and engineers have deployed and maintained observing networks for the California Department of Water Resources (DWR), for real-time monitoring of precipitation and runoff for NWS Weather Forecast Offices (WFOs) and DWR water managers.

Future Work of CIESRDS

CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Support existing and new field projects that will observe and study the water cycle in its various forms (clouds, precipitation, soil moisture) to support both NOAA Water Resource and Marine Resource Management objectives.
- Maintain and evaluate data from existing observing networks with DWR to improve quantitative precipitation estimates for the AQPI system and further weather and hydrologic model evaluation to benefit the NWS and California water management.
- Contribute to the transition of the San Francisco Bay AQPI system to operations.
- Continue work with the NOAA FACETs program to establish the use of soil moisture observations and linear inverse modeling for soil moisture forecasting. We will provide this tool for water managers to better understand and predict forecasted streamflow.
- Expand the utility of our drought-monitoring products to the fire-weather prediction community.[244]
- Play key roles in the deployment of and data analysis from the NOAA SPLASH field program, with the ultimate goal of improving weather prediction and water management in the upper Colorado River Basin.
- Collect in-situ observations from several field sites and remote sensing observations from radars and UxS. These observations will provide critical understanding of basin hydrology by observing the boundary layer, clouds, precipitation, soil moisture, and snowpack.
- Continue collaboration with the NWC on the NWM, which will involve both forecasts and use of retrospective analyses: evaluating NWM-driven soil moisture, developing soil-moisture drought-monitoring products, and probabilistic flash-flood forecasting using the time-lagged HRRR model to generate ensemble probabilities from NWM.
- Couple the Rapid Refresh Forecast System (RRFS) to an NWM Configuration of Weather Research and Forecasting Model Hydrological modeling system (WRF-Hydro) and evaluate warm-season convective forecasts.
- Examine the use of the Global Ensemble Forecast System (GEFS) to drive the NWM. We will focus on precipitation phase changes, particularly in complex terrain, examining how

the uncertainty in both observed and predicted precipitation phase transitions impacts hydrologic model forecasts for reservoir management. The knowledge gained from a focus on the U.S. West Coast will be applied to other regions with similar hydrometeorological forecasting challenges, including studies of rain-to-snow transitions in winter storms impacting the Mid-Atlantic states.
- Continue to study atmospheric rivers. Lessons learned about coastal orographic-precipitation processes, including the understanding of their impact on hydrological processes and water management, will be applied or contrasted to similar processes occurring inland.
- Continue to participate in the Hydrometeorological Testbed experiments at the NWS Weather Prediction Center (WPC) to improve understanding and forecasting technologies for extreme rainfall events, particularly using high-resolution and ensemble modeling approaches.

3.B.4.b.2 NIDIS

CIRES Background

NOAA's NIDIS was authorized by Congress in 2006 (Public Law 109–430) and reauthorized in 2014 and 2019 with an interagency mandate to coordinate and integrate drought research, building upon existing federal, tribal, state, and local partnerships in support of creating a national drought early warning information system. NIDIS's mission is to improve the nation's capacity to proactively manage drought-related risks by providing those affected with the best available information and resources to assess the potential for drought and to better prepare for, mitigate, and respond to the effects of drought. CIRES is an integral partner in the development and implementation of NIDIS. CIRES currently supports NIDIS through the 10 CIRES/CU Boulder staff who comprise the NIDIS Program Office. Other work associated with NIDIS is described in the Scientific Outreach Section, 3.B.5. Here, we focus on NIDIS research that addresses the regional impacts of climate variability, change, and extremes.

Future Work of CIESRDS

CIESRDS scientists, in collaboration with NOAA and other colleagues, will:
- Work with NOAA to develop a national drought early warning system (DEWS). NIDIS's eight regional DEWS focus their efforts within five areas: (1) drought observations and monitoring, (2) interdisciplinary research and applications, (3) drought predictions and forecasting, (4) drought planning and preparedness, and (5) communication and outreach.
- Support the development and expansion of a state-of-the-art National Coordinated Soil Moisture Monitoring Network. CIESRDS will assist NOAA colleagues with drought impact collection, analysis, and dissemination, including advancing our understanding of the economic impacts, public health impacts, ecological impacts, and wildfire impacts of drought events.
- Collaborate to improve S2S forecasting and low-flow water prediction, and to support forecast-informed reservoir operation (FIRO) strategies for water management.
- Develop an interactive Drought Planning Platform on the U.S. Drought Portal to enable planners to assess interdependent societal, climate hazard, sector, and ecological risks and vulnerabilities and to select optimal adaptation and mitigation actions.

3.B.4.b.3 Polar Processes

CIRES Background

CIRES and NOAA together have world-renowned and cross-cutting polar research capabilities. The foundation of this work is based on extensive field observations and observational analyses (e.g.,[267,268]) aimed at characterizing atmospheric processes and how they couple with sea ice, land ice, ocean, and land-surface processes.[269–272] To obtain some of these cutting-edge observations CIRES has developed targeted UxS and ground-based surface flux observing systems (e.g.,[273]). In coordination with this strong observational foundation, CIRES has developed observation-based model diagnostic tools[274] and a hierarchy of high-resolution, process, and regional modeling tools to advance understanding of polar processes.[275] CIRES co-led the MOSAiC mission, a year-long international, multi-institutional study to understand physical, chemical, and biological processes contributing to Arctic climate response in the context of rapidly changing conditions. The field phase concluded in 2020 and analysis will continue for many years. Most recently, CIRES has led the development of the CAFS to serve as a platform for knowledge synthesis, diagnostics, and model advancement.

Future Work of CIESRDS

CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Perform observations and analysis to reduce the largest uncertainties in our understanding and representation of polar regions, including mixed-phase cloud processes, precipitation and its link to moisture budgets, stratified boundary layers, multi-scale dynamics, the partitioning of the surface energy budget, and exchange processes with land, ice, and ocean.
- Compile decades of detailed observations in polar regions, including analysis of targeted field campaigns (e.g., MOSAiC), long-term observatory data sets (e.g., from Utqiagvik, Alaska; Summit, Greenland; Tiksi, Russia), and satellite observations to construct process-relationships for model assessment and diagnosis.[274]
- Conceive, design, and lead targeted polar observing activities aimed at emerging processes related to polar change and declining cryosphere.
- Contribute to the advancement of observational capabilities through further development of advanced retrieval techniques and semi-autonomous, polar-hardened observing systems including UxS and Atmospheric Surface Flux Stations.
- Examine the balances between the different coupled components (sea ice- ocean - atmosphere - land) of the climate system in the Arctic.
- Continue development of CAFS as a platform for coupled-system model advancement[276] and as a testbed for evaluation, parameterization, and advancement of NOAA's UFS

3.B.5. Scientific Outreach, Education, and Diversity

3.B.5.a. Overview

The CIRES Education & Outreach program is a well-known and trusted partner for connecting NOAA and other CIRES science with educators, learners, communities, and future scientists, and closely works with NOAA to provide the content for the climate.gov/teaching portal; (see more in Education, Section 3.D). Our communicators also work closely and continually with NOAA, CU Boulder, and other partners to help the media, policymakers, scientific colleagues, and funders understand the value of CIRES research and to encourage media coverage of our science. As an institution, CIRES is working to make DEI core elements of our systems and practices across the institute. At CU Boulder, we are leaders in supporting early-career scientists such as graduate students and postdocs, supporting their professional development with trainings, fellowships, travel and meeting support, mentoring, networking, and other programs.

CIESRDS proposes to devote considerable effort to scientific outreach, education, and diversity and include it as part of our Institute's core mission, and key to supporting research and education excellence. We describe several categories of potential projects in this section, aligned with the NOFO, to (1) improve public understanding of science; (2) improve the research enterprise, itself, through postdoctoral and visiting scientist programs (3) integrate the transformative technologies of AI, including ML; and (4) support graduate education and other early-career scientists. Underlying all projects—in this theme and others—are our efforts to improve DEI in the workforce. Here, we highlight example DEI-focused efforts, although DEI is threaded throughout all of our research and education activities and central to all we do (for example, see Appendix 4, DEI Strategic Plan; and Education, Section 3.D)

3.B.5.b. CIESRDS Proposed Work for 2022-2027 and Beyond

3.B.5.b.1 Improving Public Understanding of Science

CIRES Background

CIRES launched CLEAN, in 2010 as an NSF-funded National Science Digital Library (NSDL) Pathways project. CLEAN is now, and has been since 2012, funded by NOAA's Climate Program Office. CIRES, in collaboration with the Science Education Resource Center at Carleton College, has developed, improved, and expanded this award-winning online collection of 780+ peer-reviewed educational resources for grades K-16 and informal education.[277] With 750k annual web sessions (a measure of hits), CLEAN is the go-to resource for climate

education in the country and a leader in professional development around climate topics. The CLEAN collection is an integral part and main content provider for the climate.gov teaching portal through ongoing syndication. CLEAN supports a vibrant community of almost 1000 climate educators, the CLEAN Network. CLEAN is the founding community and backbone organization of climate change and energy transition educators in the United States and actively offers webinars and virtual meetings to its members and their networks.[278] The CLEAN team regularly engages CIRES and NOAA scientists in reviewing educational resources for scientific accuracy, leads climate education efforts at all major conferences (American Geophysical Union (AGU), Geological Society of America (GSA), American Meteorological Society (AMS), National Science Teaching Association (NSTA)), coordinates CLEAN ambassadors across the country, and partners with large education organizations and the council of state science supervisors to support thousands of educators across the country to teach about climate topics.

SOS is NOAA's flagship outreach tool, and CIRES staff have been integral to the program, enhancing scientific environmental literacy and improving understanding, value, and use of weather and water information through services to the public, including the K-12 education community. We regularly release new software versions for SOS, SOS Explorer® (SOSx), and SOSx Mobile to make the software easier to use and more engaging. Since CIRES experts began working on SOS in 2009, there have been 157 SOS installations at museums and other outreach facilities around the world, 53 SOSx installations, and thousands of downloads of SOSx Mobile—millions of learners around the world engage with NOAA and other's Earth science datasets through these platforms every year. Supported primarily by CIRES experts, the SOS data catalog has grown to over 600 datasets, including hundreds of illuminating visual displays of NOAA's Earth science data. This data catalog is continually expanding through the work of the team and our partners, including the SOS Users Collaborative Network. CIRES SOS staff support this network's annual workshops, which enable sharing of new content, technical improvements, and evaluations. The SOS team is now part of CIRES' renowned Education & Outreach program, a full-service research enterprise that develops, tests, deploys, and evaluates the impact of geoscience educational programs such as SOS. The team works in close consultation with the NOAA Office of Education, NOAA's Global Systems Laboratory (GSL), and the Cooperative Institute for Research on the Atmosphere (CIRA).

CIRES experts working embedded in NOAA groups have long made substantial contributions to NOAA's communications products and outreach efforts, writing web stories and social media posts, organizing press conferences at major conferences about cutting-edge CIRES and NOAA research, contributing data-driven animations, and crafting tour content, for example. In the last year, CIRES communicators and scientists produced or had substantial involvement in producing about one-third of the stories on NOAA Research News, and we have regularly crafted social media campaigns, e-newsletters, and engaging Story Maps, such as Listening to the Sea and Earth's Magnetic Field. CIRES experts wrote NOAA Hot Items to convey important news to internal NOAA colleagues, including agency leadership, and we supported at-home, K12 learning during COVID with online Funtastic Science Talks, Science-At-Home webinars, and webinars La Ciencia-en-Casa, reaching extensive and diverse audiences. We engage regularly with science and other journalists, pitch stories to outlets, and work with NOAA colleagues to run communications training. We have also worked to connect CIRES and NOAA scientists with opportunities to engage with the community, such as giving a talk at a Rotary Club meeting,

during the NOAA-organized Science on Tap public lecture series, or writing a syndicated essay for *The Conversation*, which may appear in newspapers around the world. CIRES explicitly includes public outreach as an annual performance measure (see Performance Measures, Section 3.F). To highlight one area, CIRES experts in the NIDIS have worked to foster excellent stakeholder communication. For example, NIDIS CIRES staff have transformed the drought.gov website into a highly user-friendly, fully accessible portal of information, including current conditions at every zip code in the country.[279] In 2021 through December 8, more than 1.1 million users visited Drought.gov, with an average of 110,239 users per month.[280] CIRES experts in NIDIS have also begun to work with Tribes to integrate Tribal Ecological Knowledge in support of increased drought early warning capacity and to expand drought information resources to reservation-specific scales.

Future Work of CIESRDS

CIESRDS, in collaboration with NOAA and other partners, will:

- Lead and facilitate the CLEAN Network in its role as a backbone organization for climate education.
- Work collaboratively to continually improve and further expand CLEAN's peer-reviewed educational resources and user base, provide content for the climate.gov/teaching portal and support broad use, integration with other climate.gov content, and dissemination.
- Provide professional development, educator newsletters, and training around climate and energy topics.
- Organize sessions at national professional meetings (e.g., the AGU Fall Meeting and Earth Educators' Rendezvous) at which CLEAN members and users present.
- Run an Ambassador program, focusing on secondary school educators who present about CLEAN to their regional science education community at conferences and workshops.
- Modernize the SOS software, adapting it to use cloud technologies for its data pipeline, unifying the backend of the product suite, and enhancing user experience through new interactive capabilities such as augmented reality, kiosk improvements, and remote app updates.
- Establish new ways of working with distributors for the promotion and sale of SOS and SOSx to ensure that distributors are properly trained and provide the necessary support to users.
- Increase interactions with SOS users and others who use the data catalog, add new visualizations through work with partners, explore novel ways of showcasing the content on new platforms, and assist users in their endeavors.
- Support the SOS Users Collaborative Network, including at user workshops. CIESRDS will also support virtual education by adapting offerings to serve learners in a changing world.
- Serve on a team of communicators involved in the Right Here, Right Now Global Climate Summit, to be co-hosted by CU Boulder and UN Human Rights in the fall of 2022.
- Work in support of easy, timely access to information about NOAA-funded accomplishments by writing and editing: news releases, web stories, social media posts, story maps, fliers, brochures, magazines, e-newsletters, and much more.
- Communicate findings and discoveries through conference presentations, peer-reviewed papers, white papers, published datasets, seminars and workshops; and outreach with schools, local Rotary clubs, churches, and other organizations.

- Conduct public tours of the NOAA facilities in the David Skaggs Research Center (DSRC) and support the public tour program with written or co-written content, including for virtual tours.
- Respond in a timely way to requests for information from elected officials and other decision-makers; and work to ensure our data and publications are accessible to all (see Data Management Plan, Section 4).
- Conduct internal communication work in alignment with NOAA's processes (e.g. OAR Hot Items) for informing leadership of upcoming high-impact or high-interest research papers and other products.
- Work to build interest in our scientists' presentations and posters at major international conferences, such as the AGU Fall Meeting and the AMS Annual Meeting.
- Contribute to redesigns and updates to NOAA websites and to various e-communications, including: maintaining a drought email alert service, regularly updating staff profiles online; modernizing publications tracking and reporting systems; collecting data and writing documents for science reviews.
- Engage the media, working with NOAA and CU Boulder, to encourage public interest and learning about our research.
- Offer regular webinars for the general public featuring updates on drought in various regions of the country and publish the monthly Dry Times, a twice-monthly e-newsletter on drought, expanding readership beyond the current 4,200 subscribers, which include scientists, the general public, journalists, and elected officials, etc. (NIDIS).
- Perform collaborative work integrating Tribal Ecological Knowledge into NIDIS' drought early warning capacity, and build out the U.S. Drought Portal to expand drought information resources at reservation-specific scales.
- Plan and run webinars and workshops, and use emerging new technologies to engage the general public, decision-makers, elected officials, and others in drought knowledge and planning (NIDIS).

3.B.5.b.2 Postdoctoral and Visiting Scientist Programs

CIRES Background
The CIRES Visiting Fellows Program (VFP) is a prestigious, competitive program designed to stimulate interdisciplinary research. Generally, we have supported about 6 new fellows annually, with about half working in NOAA groups, half in CU-Boulder-based groups. These fellows may be 2-year postdoctoral scientists and established scientist sabbatical visitors for up to a year. Our Visiting Fellows have been highly successful: for example, Antara Bannerjee, who worked in CSL from 2019-2021, published her postdoctoral work in *Nature*,[124] digging into how the Montreal Protocol has affected large-scale circulation patterns. The journal's editors named the work among the "10 remarkable discoveries" of the year.[281] Dr. Bannerjee is now a CIRES research scientist in CSL. Dillon Amaya, a Visiting Fellow in 2020-2021 who worked with campus-based Kris Karnauskas and NOAA's Judith Perlwitz on extratropical-tropical teleconnections, has recently been hired to work full-time in NOAA's PSL.

Future Work of CIESRDS
CIESRDS, in collaboration with NOAA and other partners, will:

- Run a Visiting Fellow Program to support about 6 postdoctoral research fellows annually as well as 2-6 sabbatical visitors. Our selection committee will focus on funding outstanding work that is highly interdisciplinary and aligned with NOAA's mission.
- Support these early-career researchers with professional development opportunities.
- Enhance our recruitment activities to ensure a diverse applicant pool.
- Dedicate visiting sabbatical fellowships to partners at Minority Serving Institutions (MSIs) and NOAA Cooperative Science Centers (CSCs). We will recruit sabbatical Fellows from MSIs where we have recruiting relationships, such as Howard University, the University of Texas El Paso, and UT Rio Grande Valley campuses, Florida A&M University, University of Puerto Rico Mayaguez, and University of Maryland Baltimore County, to increase the scientific interactions between CIESRDS and these partners.

3.B.5.b.3 Harnessing New Technologies: Artificial Intelligence, Machine Learning, Big Data

CIRES background
As described in the Institutional Capabilities Section (3.C.) and throughout the Research Themes here, CIRES scientists have been innovators in bringing state-of-the-art AI techniques, including ML and neural networks, into NOAA research, helping to address data analysis challenges, create efficiencies, and accelerate discovery. We have organized sessions in NOAA's Leveraging AI in Environmental Sciences workshops, presented talks there and at AGU Meetings, and shared best practices with experts across the agency, at CU Boulder, and in the Front Range Community, through organizations such as Colorado AI Research for the Environment (CARE). Our scientists benefit greatly from collaboration with CIRES' Earth Lab, a global pioneer in big Earth data analytics and teaching (see Institutional Capabilities and Composition, Section 3.C.).

CIRES scientists in GSL, for example, have experimented with several types of machine-learning models for hurricane detection in NOAA model output and satellite observations (i.e., from GOES). The ML techniques identified more regions of interest (ambiguous and active) than heuristic models and hand-labeling methods commonly used, showing great potential for improving public safety.[282] In the Space Weather arena, our scientists have literally written the book on using ML in research,[283] and are working to integrate AI techniques into electron events and other elements of space weather forecasting.

Future work of CIESRDS
CIESRDS, in collaboration with NOAA and other partners, will:
- Participate in NOAA's annual "Leveraging AI in Environmental Sciences" workshops as presenters, organizers, leaders, and learners.
- Organize AI-related workshops, trainings, and seminars and connect our researchers with AI research and training opportunities, encouraging and supporting participation.
- Draw on existing partnerships, e.g., a relationship between Earth Lab and the Department of Computer Sciences, to identify and create learning opportunities for our researchers interested in applying AI to research.
- Increase bandwidth between campus-based and NOAA-based AI expertise and foster the kind of interdisciplinary environment that allows innovation in Earth system science techniques.

- Integrate the transformative technologies of AI, including ML, into specific projects, tools, and processes described Sections 3.B.1., 3.B.2., 3.B.3., 3.B.4. and 3.B.7.

3.B.5.b.4 Supporting Graduate Education and Other Early Career Scientists

CIRES Background
CIRES is committed to the professional development of our scientists at all levels. Underlying much of our current work and the proposed work described below is an essay published by several CIRES authors in 2021,[284] which has received significant national attention. It proposes replacing the "pipeline" model of workforce development in the geosciences with a "braided river." The latter "captures the opportunity, variability, and responsiveness of a modern STEM career; that embraces the diversity and experiences of the people who engage in it; that recognizes the many on-ramps, pathways, and career pivots that real life induces; and that provides a framework in which there is a place in STEM for everyone."

CIRES currently supports graduate students with competitive research assistantships and travel grants; with a graduate association and peer mentoring program; and with professional development opportunities, including our own and others offered by CU Boulder and other partner scientific institutions. Funded by the NSF, we have offered highly rated field safety and risk management training that includes harassment training. We have also engaged graduate students and other early-career scientists in our annual science symposia, by offering a small prize to the best graduate student poster (other kinds of awards are described in Section 3.E.).

Future work of CIESRDS
CIESRDS, in collaboration with NOAA and other partners, will:
- Work to increase the number and value of the interactions between CU Boulder-based graduate students and NOAA-based researchers when student research is closely aligned with the agency's priorities. These interactions may include co-advising, shared offices and lab space at the DSRC and on campus, and administrative support from both CIESRDS and NOAA.
- Support a Graduate Association, serving the needs of (and led independently by) graduate students and postdoctoral scholars. We will provide direct support (e.g., IT and grants management) and ongoing training and professional development (e.g., communications, career development, and networking) for these early-career researchers. We will offer, annually, competitive graduate student research assistantships and travel grants.
- Support a peer-mentoring program run by employees, including training on active listening, inclusive mentorship, and other topics.
- Continually inform CIESRDS employees of HR-, proposal-, and networking-related opportunities from the CU Boulder Research & Innovation Office (RIO), including the Office of Postdoctoral Affairs, and the greater university community, including other institutes and the Office of Government Relations.
- Collaborate with the Colorado Postdoctoral Association, Colorado Leveraging Assets for Better Science (CO-LABS), a business-led consortium that promotes, educates about, and connects federally funded research in Colorado, NCAR, UNAVCO, Earth Science Women's Network (ESWN), AGU, American Geosciences Institute (AGI), and others to offer professional development trainings.

- Offer supervisor, performance review, and other professional development trainings annually to CIESRDS staff.
- Offer field safety and risk management training, including harassment.
- Provide communications and engagement training related to early-career and other scientists' use of social media and engagement with broader audiences (eg, journalists, policymakers); and link our scientists to complementary trainings offered by others across campus and the Front Range science ecosystem.

3.B.5.b.5 Improving Diversity, Inclusion, and Equity in the Workforce

CIRES Background
CIRES has had strong success mentoring and supporting students and scholars from underrepresented backgrounds through a steadily increasing array of programs that we either run (e.g., the Research Experiences for Community College Students (RECCS) program, Earth Data Science Corps, and the Tribal Climate Leaders Program, described in Section 3.D.1.) or participate in (e.g. NCAR's Significant Opportunities in Atmospheric Research and Science (SOARS)). We have also created and shared widely a short *Inclusive Hiring Guide* and led strategic planning, trainings and workshops across CU Boulder to train employees in anti-racism, bystander intervention, and more. These efforts not only align with NOAA's education[25] and diversity[26] goals, but they have also given us the expertise to develop effective, meaningful programs.

Future Work of CIESRDS
CIESRDS work will enhance and contribute to NOAA's mission to create a measurably more supportive culture for underrepresented students and trainees within the DSRC and elsewhere, to better retain those individuals during education and career transitions, and to improve clarity for students and early-career researchers about how to continue working with NOAA in a professional capacity. CIESRDS will include robust program coordination and evaluation support of all of our activities.

For CIESRDS, we propose to collaborate and interact with NOAA's CSCs, Experiential Research and Training Opportunities (NERTO), Postdoctoral Fellowships, and the agency's EPP/MSI undergraduate scholarships. We will work to help NOAA meet its workforce and hiring goals.[26] CIESRDS will develop programming to provide clear pathways to employment and inclusive mentoring to support career transitions for students and Early Career Researchers (ECRs) who participate in NOAA EPP/MSI programs, increasing the likelihood for these scientists to persist in the NOAA mission science and to transition into careers with NOAA. We will develop mechanisms for CIESRDS scientists to develop relationships with the faculty at the NOAA EPP/MSI institutions in order to develop cross-organizational research projects and co-advising arrangements.

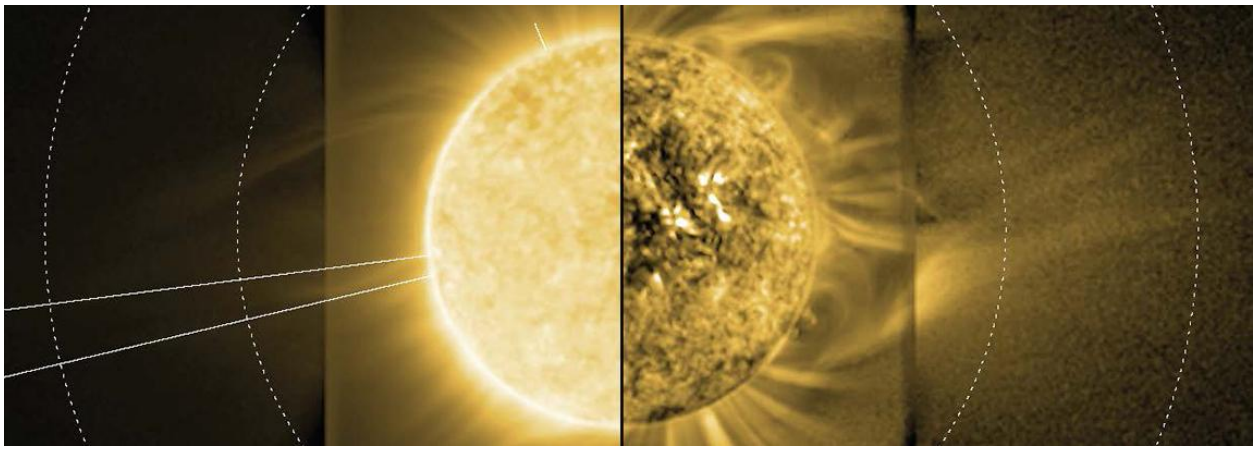
We will focus on MSIs from which we currently receive significant numbers of internship applications, such as Howard University, the University of Texas El Paso, and UT Rio Grande Valley campuses, Florida A&M University, University of Puerto Rico Mayaguez, and University of Maryland Baltimore County. In addition, we will support a tribal engagement expert to develop relationships between CIESRDS and Tribal Colleges and Universities, such as Oglala Lakota College and United Tribes Technical College.

CIESRDS will build upon the robust foundation that CIRES has created and integrated across its entire organization and enhance the Diversity and Inclusion (D&I) of its workforce. Much of this work is integrated within the entire organization, and all work will be done in alignment with our institute's Diversity & Inclusion Strategic Plan (Appendix 4). If funded, CIESRDS will develop a strategic plan by 2023, including JEDI plans and goals.

CIESRDS will:

- Run a summer internship program for undergraduate and graduate students from MSIs to work within NOAA GSL, and will expand this to other DSRC Labs. We will focus our recruiting efforts on the MSIs that are part of the NOAA CSCs as described elsewhere.
- Recruit new graduate students and employees from diverse backgrounds in collaboration with or during conferences of: the National Association of Black Geoscientists, the Society for Advancement of Chicanos/Hispanics and Native Americans in Science, and the American Indian Science and Engineering Society.
- Partner with three NOAA CSCs, the National Center for Atmospheric Sciences-M led by Howard University, the Center for Earth System Sciences and Remote Sensing Technologies, led by The City College of The City University of New York, the NOAA Center for Coastal and Marine Ecosystems, led by Florida A&M University, to recruit JEDI graduate students and employees. Partnerships will include providing professional development as part of CSC student programming, developing cross-program recruiting relationships (learning pathways) and the relationship-building activities described below.
- Initiate and strengthen relationships between NOAA CSC faculty and CIESRDS researchers embedded in NOAA, resulting in increased collaboration and increased positive supports for CSC students and faculty. CIESRDS will build mechanisms to increase relationships between CSC faculty and CIESRDS researchers (e.g., networking lightning talks, site visits).
- Develop a faculty exchange program, where CSC Faculty and students come to work within CIESRDS and NOAA partners in Boulder, and CIESRDS scientists may visit CSC institutions to support teaching, mentoring, and research needs.
- Increase our ability to engage and support underrepresented students to succeed in research opportunities at the DSRC. We will accomplish this with new infrastructure to provide the positive supports known to increase recruitment and retention of underrepresented students in geosciences,[285,286] building upon existing grass-roots CIRES mentoring relationships and supporting mentors and students systemically.
- Draw on existing expertise to engage Tribal colleges and universities and to support Tribal students who participate in internships or other opportunities.
- Expand existing and develop new CIESRDS-led research experience programs at NOAA. As part of this effort, we will increase internship participation through new relationships with Tribal colleges and universities.
- Collaborate with EPP/MSI faculty and CIESRDS researchers to define a portfolio of well-calibrated projects for EPP/MSI, NOAA Postdoctoral Fellowship, NERTO, and other interns at all higher education levels. We will focus on faculty that have NOAA Boulder related scientific interests, such as at Howard University and University of Texas El Paso.
- Partner with CSCs to develop and support undergraduate recruitment and college readiness programs for high school students.

- Provide professional development and positive support for interns and scholars, including onboarding, weekly support and cohort building, access to affinity groups and resources, and summer workshop training.
- Provide inclusive mentoring[287] and professional development training for CIESRDS mentors to help them mentor across differences without asking students to assimilate or code-switch.
- Maintain regular communication with students throughout their educational career to help them transition within the suite of intersecting opportunities[288] and help successive cohorts.
- Encourage deepening skills of all CIESRDS members and collaborators in JEDI and ensure compliance with all required training, through:
  - Promoting and supporting JEDI professional development. Past examples include facilitated discussion through CU Boulder Coursera Anti-Racism I course, training in difficult conversations, inclusive hiring practices, supervisor training, interpersonal skills, and inclusion for different identity groups;
  - Institute-wide and inter-institute community-of-practice groups and employee resource groups (affinity groups);
  - Recognizing diversity and inclusion contributions in performance assessments;
  - Systematizing and scaling inclusive hiring practices; and
  - Monitoring employee completion of required University DEI training.



3.B.6. Space Weather Science and Prediction

3.B.6.a. Overview

NOAA's SWPC is the nation's source of space weather forecasts and information for reducing the impact of solar events on the Earth and the surrounding space environment. These services will become increasingly critical as the Sun transitions from the recently declared Solar Minimum to Solar Maximum and the frequency of space weather events increases.

CIRES scientists and developers have been instrumental to SWPC's successes, streamlining data processing and transitioning models and other technologies from research into operations to ensure users receive timely, actionable space weather information. CIESRDS will take advantage of this experience and expertise to pursue activities that further advance the space weather enterprise for NOAA and beyond, ultimately serving decision-makers who seek to mitigate the significant societal, economic, health, and national security impacts of severe space weather.

Potential CIESRDS projects below are divided into four categories: (1) Observations; (2) Model Development, Validation, and Evaluation; (3) R2O2R: Space Weather Testbed; and (4) Modernizing SWPC's Space Weather Forecasting Office.

3.B.6.b. CIESRDS Proposed Work for 2022-2027 and Beyond

3.B.6.b.1 Observations

CIRES Background
Continuous, real-time observations of the Sun and the solar wind are vital for NOAA NWS SWPC forecast operations. For many years, CIRES scientists have worked with Federal collaborators in SWPC to obtain and process ground- and space-based observations. On the ground, the six identical Global Oscillation Network Group (GONG)[289,290] network sites provide white light imagery and magnetic field maps of the Sun's photosphere every minute, as well as H-alpha imagery of dynamic activity in the Sun's chromosphere (e.g., solar flares). Every hour, tens of thousands of magnetic field maps from the past solar rotation are combined into the global synoptic maps that drive the Wang-Sheeley-Arge (WSA)-Enlil model of the solar wind and determination of coronal mass ejection arrival times[291–293] for SWPC forecast operations. CIRES scientists have a history of successful collaboration with NOAA and other partners to successfully transition this data processing from the National Solar Observatory into operations at SWPC in 2021. Efforts to document, assess, and improve the data products will continue in subsequent years; the work is currently led and primarily conducted by CIRES staff. Additionally, planning is currently underway for a future ground-based solar observing network to replace the aging GONG system and meet SWPC's future operational needs as part of Action 2.2 of the National Space Weather Strategy and Action Plan.[294] CIRES researchers are leading this effort for NOAA, in partnership with the agency.

In space, the Deep Space Climate Observatory satellite, launched in 2015, will continue to provide solar wind observations at the L1 Lagrange point until at least 2025, when it will be replaced by the more comprehensive instrument suite on NOAA's SWFO satellite. The SWFO-L1 Compact Coronagraph will provide near real-time imaging of coronal mass ejections. Measurements from the Solar Wind Instrument Suite—consisting of the Magnetometer, Solar Wind Plasma Sensor, and SupraThermal Ion Sensor instruments—will be used to identify the signatures of coronal mass ejections, co-rotating interaction regions, and interplanetary shocks—all drivers of space weather impacts at Earth.

Future Work of CIESRDS
CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Develop forecast applications and visualizations for the analysis of new satellite data, to aid estimations of the arrival time and strength of coronal mass ejection shock and ejecta, drivers of geomagnetic storming effects that can impact the electrical power grid; and the radiation environment to which spacecraft are exposed. We will develop and improve forecast tools with these data to detect and determine the direction and propagation speed of these eruptive events, in support of SWPC's numerical solar wind modeling and geomagnetic storm forecasts.
- Develop warning systems that have the potential to increase SWPC lead time for radiation storm products serving the satellite, aviation, and human space exploration industries. We will use Suprathermal Ion Sensor energetic electron measurements, which are expected to serve as a precursor for high-energy protons in solar radiation storms, to create a

RELativistic Electron Alert System for Exploration (RELeASE)-style warning system for protons.[295–297]
- Lead the effort to develop new numerical models and applications for analyzing, interpreting, and combining the data from the significant expansion of the number of NASA and European Space Agency satellite platforms observing the Sun and the solar wind for maximum advantage.

3.B.6.b.2 Model Development, Validation, and Evaluation

CIRES Background
CIRES researchers and developers in SWPC have long led and contributed to modeling efforts critical in space weather forecasting, including the WSA-Enlil model, which has been used to model the solar wind and coronal mass ejection arrival times for nearly a decade. University of Michigan scientists developed the Geospace model, which provides a forecast for geomagnetic activity in response to the solar wind,[298] and CIRES scientists were instrumental in the transitions to operations of the original code and an upgrade this past year. The model drives the geoelectric model for geomagnetically induced currents (GICs), and for perturbations of the ground magnetic field at regional level.[299] CIRES scientists developed the WAM-IPE model,[300–303] which National Centers for Environmental Prediction (NCEP) Central Operations (NCO) made operational in 2021. SWPC uses WAM-IPE to predict ionospheric perturbations, which can disrupt radio wave propagation, impacting communication and navigation. CIRES scientists have led the assimilation of COSMIC-2 radio occultation (RO) data into the global assimilative total electron content model (Glo-TEC) to augment the ground-based GNSS networks to improve specification of ionospheric plasma. In recent years there has been a growing desire from the satellite, aviation, and human space exploration industries for solar radiation storm forecast products and services. In November 2019, CIRES scientists and NOAA colleagues launched new space weather advisories tailored for the International Civil Aviation Organization (ICAO). To support these ICAO advisories, CIRES scientists played a pivotal role in transitioning the Federal Aviation Administration Civil Aviation Research Institute-7 aviation radiation model [304] into operations at SWPC.[305]

Future Work of CIESRDS
CIESRDS scientists, in collaboration with NOAA and other colleagues, will:
- Use the Air Force Data Assimilative Photospheric flux Transport (ADAPT) model [292] to assimilate GONG data and provide more accurate input boundary conditions for the WSA-Enlil model. This implementation of ADAPT will also facilitate the use of helioseismic maps of the magnetic field on the Sun's far-side, which will help NOAA space weather forecasters to include, earlier, information from active regions newly formed on the side of the Sun facing away from the Earth, mitigating the impact of discontinuities associated with their current abrupt appearance on the visible disk.
- Implement a long-anticipated WSA version upgrade that will enable the switch to improved GONG data products that include corrections to the magnetic field zero point resulting in more accurate determination of coronal hole boundaries.
- Couple regional ground magnetic perturbations, as forecast by the Geospace Model, with detailed mappings of both 1D and 3D regional ground conductivity to produce a regional forecast of electric field activity over the continental United States and, eventually, Canada. The resulting regional Geoelectric Model will provide longer forecast lead times.

- Evaluate the use of a gray-box approach (combining the output of the Geoelectric model and ML approaches) to improve the accuracy of the Geoelectric model. Recently, CIRES demonstrated that coupling the output of the Geospace model with a ML algorithm can improve predictions for the rate of change of the Earth's magnetic field.[306]
- Explore transitioning the current forecasting products to a probabilistic framework, by specifying the uncertainty associated with predictions and estimating how such uncertainties can propagate within and between models.
- Upgrade hemispheric asymmetry and erosion and increase the current horizontal resolution of WAM and IPE from more than 200 km to 50 km to resolve more of the spectrum of ionospheric structure and predict the likelihood of ionospheric irregularities. Upper atmosphere expansion in the WAM can improve the ability to simulate satellite drag, orbit prediction, collision avoidance, ultimately improving space traffic management.
- Work to identify a path to move from the current core to the FV3. FV3, now used in the U.S. Global Forecast System weather model, would represent a significant upgrade to the WAM-IPE space weather model.
- With NOAA colleagues, experiment with coupling the WSA-Enlil, Geospace, and WAM-IPE models to follow the transit of solar disturbances "from Sun-to-mud." WSA-Enlil forecasts of solar wind conditions can drive the Geospace model a day or two in advance, and the Geospace model, in turn, can provide the geomagnetic activity drivers of WAM-IPE, to predict the impact of solar and geomagnetic variability on the ionosphere and thermosphere.
- Ingest commercial RO data into space weather forecasting, now that its value has been validated—commercial RO data offer measurements in regions not otherwise surveyed. We will evaluate the COSMIC-2 ionospheric irregularity product for use in space weather operations, and assimilate all available RO data into the Rate-of-change of TEC Index (ROTI) model, which, together with Glo-TEC, is an operational product of the International Civil Aviation Organization.
- Develop a forward model for the in-situ COSMIC-2 ion density. The assimilative models augmented with COSMIC-2 and commercial RO[307,308] data will provide improved specification and forecasts of plasma density, in order to mitigate the impact of structure in the ionospheric on operational radio wave systems.
- Continue development and validation of the simulated radiation environment at aviation flight levels, necessary to improve the accuracy of these models. Inclusion of the new Badhwar-O'Neill 2020 galactic cosmic ray model[309] may be considered and improved methods of specifying the geomagnetic particle cutoff rigidities investigated.
- Build a catalog of reanalyzed historical radiation storm events to support forecaster training and drive end-user, table-top exercises with partners in the aviation industry.
- Investigate automatic generation of ICAO advisories, to signal forecasters when an advisory may be warranted. These "first-guess" ICAO advisories would help simplify message formation and enable more efficient, timely advisories.
- Work to develop, validate, and transition the next-generation solar energetic particle forecast models to improve SWPC's radiation storm products, which are essential for safe human spaceflight, as it has since the days of Gemini and Apollo.

3.B.6.b.3 R2O2R: Space Weather Testbed

CIRES Background
NOAA is currently responding to the Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act.[310] PROSWIFT requires departments and agencies to develop formal mechanisms to transition space weather models and capabilities into NOAA's NWS operations, supporting a Weather-Ready Nation. NOAA SWPC and NASA are collaborating to develop an Architecture for Collaborative Evaluation (ACE),[311] which has begun to make operational model output available to the community. CIRES researchers have contributed to these efforts, making initial progress with the Glo-TEC and WSA-Enlil models, for example.

NOAA NWS is developing a Space Weather Prediction Testbed and co-locating it with SWPC as a key component of a formal **R2O2R** mechanism. CIRES scientists have supported this testbed and CIESRDS will in the future. This work will be guided by a formal framework to ensure that research, observations, and model advances supported by NASA, NSF, and the Department of Defense are integrated into NOAA operations, ensuring the Nation benefits from significant investments in space weather research.

Future Work of CIESRDS
CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Develop and evaluate new Space Weather Forecast Office models and products to engage the user community in testbed experiments. This effort will allow forecasters to more easily share new products for feedback, encourage collaboration, and prioritize improvements.
- Contribute to the evaluation of forecast models, visualizations, and other tools in the ACE and testbed environments and the transition of these capabilities to SWPC operations.
- Operationalize model storage solutions to identify effective solutions for robust storage and dissemination of operational model results, including results from validation efforts illustrating model version advancements. This would alleviate issues surrounding retrospective analysis, machine-learning model development, and general data access, and would also expedite and enhance O2R projects.
- Support long-term SWPC visualization solutions and standards. This will include supporting the (a) establishment and validation of visualization standards to make SWPC products more useful, recognizable, supportable, and efficient; (b) selection of high priority forecaster tools and products; (c) implementation and evaluation of visual improvements and deployment to operations; and (d) selection of high priority public products and collection of customer feedback.

3.B.6.b.4 Modernizing SWPC's Space Weather Forecasting Office

CIRES Background
The CIRES team has contributed to the modernization of SWPC forecasting capabilities by both implementing several new forecast tools and improving the existing SWPC forecasting framework. Two examples of new forecasting tools may be found in the operational ICAO system[312] and in creating a 3-D version of the regional Geoelectric model in operations. Transitioning a 3-D model to operations allowed SWPC to provide a more intuitive forecast for the ground conductivity of space weather storms, affecting geo-magnetically induced currents in the power grid.[313]

Future Work of CIESRDS

CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Make key improvements to space weather forecasting tools, e.g., The Solar Command Center (SCC) application used to produce 3-hour products containing geomagnetic indices, with the current NOAA scale conditions and with the next day's predictions. We will upgrade the SCC to improve forecaster usability and increase its operational reliability.
- Support use of new images from coronagraphs aboard SWFO-L1, GOES Compact Coronagraph (CCOR), and other missions. We will also investigate the possibility of operationalizing recent research extending the coronal mass ejection analysis tool (CAT) field of view using heliospheric imager data on Solar Terrestrial Relations Observatory (STEREO)-A (and possible future L5 missions).[314]
- Implement other critical, planned tool improvements include replacing The Weekly,[315] replacing the Solar Region Summary (SRS),[316] replacing the Alerts Timeline,[317] and removing the Interface Definition Language (IDL) dependencies in several forecast product generation systems.

3.B.7. Weather Research and Forecasting

3.B.7.a. Overview

The 2018 Weather Research and Forecasting Innovation Act of 2017 created a focused program of investment to substantially improve weather forecasting and the prediction of high-impact weather events. In response, scientists and developers from NOAA and many partner institutions, including CIRES, have contributed to the Earth Prediction Innovation Center (EPIC), and UFS—the first, to accelerate community-developed enhancements into NWP operations, and the second to serve as a community-based, coupled and comprehensive Earth modeling system. Both promise to accelerate the transition of research into operations, improve weather forecasting measurably, and serve weather forecasters with key tools, including forecast dissemination tools. CIRES has been foundationally involved in these efforts and has a long record of successfully transitioning research innovations into practical systems that support a resilient, Weather Ready Nation. Our work in this area has encompassed advanced observing systems, data assimilation (e.g., Meteorological Assimilation Data Ingest System (MADIS)), high-performance computing including ML, coupled models and ensembles, and dissemination tools. Below, we describe potential work in four relevant topical areas associated with weather research and forecasting: (1) Improved Modeling Capabilities, (2) High Impact Weather, (3) Data Assimilation, and (4) Computing and Disseminating Tools. Proposed CIESRDS projects often overlap and complement each other, across themes. Research discussed in Climate Science and

Prediction (Section 3.B.2.) and Regional Science and Applications (3.B.4) also address the needs of this theme.

3.B.7.b. CIESRDS Proposed Work for 2022-2027 and Beyond

3.B.7.b.1 Improved Modeling Capabilities

CIRES Background

CIRES has played an integral role in developing NOAA's Next-Generation Global Prediction System, from participating in the selection of the new finite-volume dynamical core to developing advanced data assimilation algorithms (e.g.,[318–320]), new deterministic and stochastic physics schemes (e.g.,[193,321–323]), and reanalysis/reforecasting products (e.g.,[172,323,324]). All of these components have significantly contributed to the advancement of the UFS, NOAA's next-generation community-based, coupled comprehensive Earth system modeling system. An emphasis of some work has been on S2S prediction timescales, which range from a few weeks to months or years. Examples include the development of improved S2S precipitation forecasts in the U.S. West and sub-seasonal forecasts of hurricane activity in the Atlantic Basin (e.g.,[325]); week 2 fire weather prediction based on post-processing of reforecasts and the development of machine-learning algorithms for weeks 3-4 precipitation across the United States, with intended transition to CPC;[326,327] integration of AI and ML and other data-driven methods with data assimilation to support coupled data assimilation (CDA) and S2S prediction.[328–331] The investigation of stratosphere-troposphere coupling as a source of S2S predictability and a contributor to climate extremes.

CIRES and partners developed the first rapidly updating models and were successful in the first assimilation of radar reflectivity, commercial aircraft, and cloud data in the United States. More recent successes are NOAA's RAP and HRRR hourly high-impact weather prediction models; final versions went into NWS operations in December 2020.[332] Three high-resolution regional smoke forecast models also transitioned to operations in 2020,[333] including the HRRR-Smoke at 3km resolution over CONUS. Finally, CIRES researchers played a critical role in developing the coupled global weather and air chemistry Global Ensemble Forecast System-Aerosols (GEFS-Aerosols) that went into operations September 2020.[314, 334] The model produces 7-day forecasts for a host of air-quality impacts including dust, soot, and other respiratory hazards.

Future Work of CIESRDS

CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Accelerate the development of advanced physics parameterization schemes for the UFS. This includes the development of experimental physical parameterizations, making new components modular in design, and ensuring that they are properly coupled to other components of a next-generation physics suite supporting the UFS.
- Improve the representation of aerosol impacts on parameterized clouds and their interaction with radiation, important for weather and climate forecasting. We will update convection and radiation parameterizations to include aerosol impacts from shallow and warm rain congestus and results from global model simulations will be compared to observations during field experiments as well as Large Eddy Simulations (LES).
- Develop diagnostics and metrics to evaluate NOAA models to help developers and forecasters evaluate key processes and their predictors.

- Post-process reforecasts to improve the National Blend of Models precipitation forecasts and develop methods for accurate spatiotemporal modeling of post-processed forecasts.
- Collaborate across NOAA, specifically with GSL, PSL, and the EMC, to implement various updates/improvements to the UFS modeling system to produce a sub-seasonal forecast system that will replace the current operational Coupled Forecast System model version 2 (CFSv2).
- Contribute to the Developmental Testbed Center, which is working to improve operational NWP by connecting the research community to the NWS, accelerating the transition of innovations to operations.
- Develop and transition to operations the next convection-allowing regional ensemble model using the foundational UFS Short Range Weather Application, known as the RRFS. The RRFS will be demonstrated in the NOAA Hazardous Weather Testbed and the NOAA Hydrometeorological Testbed experiments.
- Test additional satellite observations for radiance, atmospheric motion vector, and FRP, plus geostationary lightning mapper observations for model improvements for testbed demonstrations. We will also include extreme rainfall diagnostics including rain rate and annual recurrence interval conversions within the RRFS.
- Replace the operational High-Resolution Ensemble Forecast system with RRFS-Ensemble using the FV3 dynamical core and provide forecasts with 10 members and convection-allowing, 3-km grid spacing out to 60-h lead time 4 times per day. Ensemble members will employ initial- and boundary-condition perturbations, stochastic physics, and possibly multiple physics packages. We will demonstrate the RRFS-Ensemble in testbeds during the warm season.
- Develop and test an experimental global rapid refresh capability (Global RAP) to determine the final configuration in support of the GFS. Our objective is to advance from the current 6-hour cycle GFS forecast to an hourly cycled forecast system. We will develop and test physics enhancements to improve both short-term and longer-term forecasts (1-2+ weeks).
- Integrate the highly acclaimed HRRR-Smoke model capability into the RRFS based on the FV3 core. We will include smoke and aerosol emission modules in the Common Community Physics Package (CCPP). We will support the transition to operations of the RRFS-Smoke, which will include higher spatial resolution and use the FV3 dynamical core.
- Support the introduction of RAP-Chem/GSL packages in the next community WRF-Chemistry model release, enabling the simultaneous simulation of atmospheric chemistry and dynamics in a NWP model.
- Develop and evaluate the NOAA RRFS/CMAQ Inline System at NOAA.
- Work to expand regional FV3 core capabilities for various scales of applications to further advance the development of a regional model that will match and exceed existing NCEP-operational regional system capabilities.
- Contribute to the development of NOAA weather and aerosol forecasts that can be converted into time-series data for any location.
- Collaborate with the disease modeling community to enable further use of NOAA's environmental intelligence capabilities for infectious disease modeling and pandemic preparedness: climate data; observing systems, and short- and long-term predictions; and other possible opportunities for improved use of environmental data.

3.B.7.b.2 High-Impact Weather

CIRES Background

CIRES employees have been involved in numerous developmental projects and experimental testbeds. These projects focus on providing forecast tools to streamline, inform, and improve the forecasting activities at the NOAA WPC and its partners. CIRES has several flash flood-related projects including the Extreme Precipitation Forecast Table,[335] developing a flash-flood verification system,[336] assessing heavy precipitation model bias,[337] developing a maximum rainfall and timing product, and ensemble cluster analysis.[338] Winter weather projects include the Winter Storm Severity Index, forecasting precipitation type, and forecasting maximum snowfall and timing. Several projects are also concerned with quantifying, for forecasters, how anomalous a forecast is given a model climatology, and CIRES scientists have helped create "hourly wildfire potential," an index derived from the HRRR model predictions of temperature, winds, and soil moisture conditions. Moreover, CIRES scientists have long supported decision-support and data-delivery tools important in high-impact weather situations; these are further described in this Section: Computing and Disseminating Tools (Section 3.B.7.b.4.).

Future Work of CIESRDS

CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Facilitate and coordinate the WPC's Hydrometeorology Testbed, building off of previous experiments by testing experimental products from NOAA partners and developing novel verification products in-house. One such project may involve the utilization of model data to develop a ubiquitous hazard model with multiple partners.
- Improve model output through post-processing (object-based approaches, statistics bias correction, statistical calibration, and ML) for extreme weather events and the development of forecast dissemination tools related to heavy precipitation and flash flooding.
- Expand flash flooding development projects by adding additional WPC forecast products to the verification system, providing heavy rainfall object-based biases to forecasters, and improving upon ensemble cluster analysis by experimenting with other clustering methodologies and variables.
- Experiment with ML methods to classify unique heavy precipitation objects and improve ensemble clustering methods.
- Contribute to WPC web development as a method of transitioning R2O.
- Contribute to the WPC Advanced Weather Interactive Processing System (AWIPS) development.
- Expand research related to identifying potentially extreme weather events in forecast models (e.g., Ensemble Situational Awareness Tables and Weather-in-Context) to include additional high-impact variables.
- Improve the Winter Storm Severity Index over the CONUS and expand it into Alaska by utilizing a climatology for that region.
- Pursue projects utilizing model and observational data to help forecasters identify specific upcoming extreme weather events (e.g. atmospheric river, cold air, etc.) through non-traditional data analysis (e.g., AI/ML, object identification & tracking software).
- Provide key expertise to develop Hazard Services, a new software platform or architecture developed for NWS forecasters to better issue severe weather watches, warnings, and advisories (WWAs) to the public. We will consolidate and customize WWA software products to streamline NWS operations, and develop other WWAs for hazards related to winter weather, marine weather, tornadoes, thunderstorms, fires, heat, dust, wind, civil

emergencies, etc. Some of these applications will be adapted for use in NWS National Centers and international weather agencies.
- Integrate Probabilistic Hazards Information (PHI) into Hazard Services in support of FACETs to improve situational awareness of impending storms. This will provide users with uncertainty information for decision support.
- Contribute to "Threats-In-Motion" (TIM), a warning dissemination approach for AWIPS that would enable NWS forecasters to enhance severe thunderstorm and tornado warnings.
- Provide a system for the AWIPS Tsunami Operations Messaging Service (ATOMS) to generate consistent Watch/Warning/Advisory products for the NWS Tsunami Warning Centers. This will provide a quicker response time for the protection of life and property.
- Develop an experimental Impact-Based Decision Support Services (IDSS) Engine, a cohesive system for meteorologists providing end-to-end capabilities that support the IDSS process consistently across the NWS while still allowing for customer-specific messaging.
- Prototype an IDSS Tool for the U.S. Department of Transportation (DOT) to determine the impact to road segments for high wind and ice. This tool will allow the DOT Bureau of Transportation Statistics to examine the vulnerability of the national transportation system to adverse weather.
- Serve GSL's Quality Assessment Product Development Team, working to ensure that aviation weather products developed through the Federal Aviation Administration's Aviation Weather Research Program (AWRP) are scientifically accurate and provide value to the individual decision-maker within their operational aviation decision processes. CIESRDS scientists will contribute scientific research, coordination with other Product Development Teams and stakeholders, software development, data collection, processing, analysis, and reporting—in support of evaluations.

3.B.7.b.3 Data Assimilation

CIRES Background
CIRES scientists have been key contributors to observational and data assimilation activities across NOAA. For example, we have taken on project leadership roles in transitioning research—in data assimilation (DA) and model physics—to operations as part of the UFS Research to Operations project (UFS R2O). CIRES scientists, in collaboration with NOAA and other colleagues, collect, build and archive national datasets through the development and support of MADIS. MADIS fills gaps in NOAA's observational infrastructure and reduces costs to the agency by centralizing data acquisition and reducing redundancy. MADIS was transitioned to operations in 2015, but research and development continues with new releases delivering high-quality data to meteorological centers worldwide.[339] MADIS processes 71M weather observations each day, 2.9M each hour, and 750,000 automated commercial aircraft observations processed each day.

Future Work of CIESRDS
CIESRDS scientists, in collaboration with NOAA and other colleagues, will:
- Improve DA methodologies for the atmosphere, ocean, sea-ice, ocean waves, and land-surface initialization—including soil moisture and snow. This work will support technical developments for the initialization of the UFS using the Joint Center for Satellite Data Assimilation (JCSDA) Joint Effort for Data Assimilation Integration (JEDI) software

framework. This project will generate the next-generation reanalysis and reforecast products suite. Key to this work:
  - Implementation of cloud-computing platforms,
  - The development of the science and infrastructure of an ensemble-based strongly coupled cycling data assimilation system, and
  - Research into the value of ML and more frequent cycling (e.g., hourly).
- Assimilate aerosol optical depth observations within the Community Atmosphere Model (CAM)-CMAQ Model. Couple the FV3 and the Stand Alone Regional CAM.
- Add a 3-dimensional capability to the Real Time Mesoscale Analysis System (RTMA) and transition this tool to operations, enabling 2D fields to be better diagnosed from the 3D analysis; the 3D analysis will help with intrinsically-3D fields like clouds.
- Advance data assimilation concepts and techniques by applying AI to identify and correct model and observation errors, contributing to community-based data assimilation systems, and exploring how computing systems could efficiently assimilate vast amounts of observations into CDA systems.
- Develop the National Global Data Assimilation Ensemble-based System for forecasting aerosols.
- Apply ML to analyze and extract the most important information from GOES satellite observations to be used in data assimilation systems, focusing first on feature or object detection to identify typhoons or hurricanes, and progressing toward more complex problems such as identification of cyclogenesis, and convective initiation, estimation of surface water, and bias correction.
- Lead the development of RRFS-SMOKE to ingest hourly GOES-16/17 and Visible Infrared Imaging Radiometer Suite (VIIRS) satellite observations. We will assimilate the VIIRS Aerosol Optical Depth (AOD) observations and surface PM2.5 measurements from the Air Now network within the model framework. We will develop an ensemble aerosol assimilation system using high-frequency AOD data from GOES-16/17 with this system.
- Develop CDA methods for initializing NOAA's coupled forecast models, particularly targeting S2S prediction timescales (3-4 weeks to a year).
- Integrate AI/ML with data assimilation to improve forecast model initialization, and develop AI/ML and statistical post-processing to enhance the skill of S2S guidance related to fire weather, renewable energy, weeks 3-4 precipitation, and hydrological prediction.

3.B.7.b.4 Computing and Disseminating Tools

CIRES Background

CIRES has been a key NOAA partner in improving the computational efficiency of models and the utility of their outputs. CIRES has contributed to the NOAA goals to be exascale ready by contributing to the development of advanced data storage and delivery, exascale High Performance Computing (HPC), and models that can be applied using these new technologies, moving NOAA towards increased scientific accuracy while improving computational efficiency. For example, CIRES scientists have contributed to the long-term research efforts to determine how to develop and run 1km-resolution models with data assimilation more efficiently on computer systems with millions of processors. Further, CIRES experts have worked to help NOAA identify and implement new technologies, methods, and capabilities for web-based visualization, processing, and interaction with exascale data efficiently. CIRES has also worked

with NOAA partners to explore and implement cloud-computing services in support of NOAA's objectives.

CIRES' contributions to NOAA decision support tool development began in the early 1980s with AWIPS and is continuing now with incremental deployments of GSL's Hazard Services system to NWS offices. Hazard Services streamlines NWS watch, warning, and advisory-related services into one interface and can be customized for each office, region, or type of weather. In GSL, we are collaborating to advance the Weather Archive and Visualization Environment (WAVE) project, a web-based multi-purpose system where NWS forecasters create impact-based graphics about weather hazards to deliver via their websites and social media. Examples of CIRES contributions to efforts to understand how weather information is used include: development of a prototype RRFS, based on the UFS framework, which is currently being used in the cloud to make ensemble forecasts; evaluation of the Prototype RRFS Ensemble Forecasts with cloud HPC at NOAA Testbeds; development of tools to detect tropical and extratropical cyclones using deep learning;[282] application of deep learning to nowcast the spatial coverage of convection from Himawari-8 satellite data;[340] and design of a ML random forest tool to make an hourly FRP value using weather and satellite data together to improve FRP modeling.

Future Work of CIESRDS

CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Investigate new technologies, methods, and capabilities for web-based visualization, processing, and interaction with exascale data efficiently in support of research. We will work with NOAA to enable remote work with these data and will investigate and implement cloud computing services, when deemed reasonable.
- Investigate cloud computing as an alternative platform for running and testing RRFS to ensure a speedier delivery of the evaluation of RRFS. The use of the cloud has the potential to both alleviate the over-use of the current NOAA operational and research problems, and to expand the resources available to vital NOAA modeling research, speeding the process of operational upgrades significantly.
- Develop and demonstrate GeoFLuid Object WorkBench (GeoFLOW), a spectral element library that allows rapid development of computational models relevant to problems of weather modeling and atmospheric science. This will create a prototype cloud-resolving prediction model producing real-time predictions on exascale HPC.
- Contribute to the Software Engineering for Novel Architectures (SENA) project, which is exploring new programming paradigms to advance operational prediction models such as the GFS, RRFS, and JEDI. Approaches being explored include modeling frameworks, libraries, languages, and directive-based approaches designed to improve performance portability across central processing unit (CPU), Arm and graphics processing unit (GPU) based HPC systems. We will also explore cloud computing targeting HPC systems. We will pursue research to evaluate the cost of commercial cloud versus traditional NOAA HPC performance and examine the tradeoffs with containerization versus alternatives.
- Develop methods for adding new providers to NWS operations in weeks instead of years and will add improvements to delivering information to users.

3.B.8. Science and Predictions to Support Ecosystem Research

3.B.8.a. Overview

Essential to the evaluation of ecosystem health is a basic, physical understanding of the changing environment; CIRES scientists excel at this type of research and will bring our experience and expertise to CIESRDS to analyze physical systems and develop insights, predictions, and projections that are fundamental drivers of ecosystem processes and critical to ecosystem management. In collaboration with other scientists, CIESRDS scientists will meet the explicit needs of NOAA laid out in the NOFO to produce high-resolution, multi-decadal Earth system model projections for assessing climate impacts on both marine, terrestrial, and coastal ecosystems. We will use downscaling techniques to obtain results at finer resolution than global climate modeling can provide, and will collaborate with others to project ecologically-relevant variables. CIESRDS will continue to publish research results traditionally, and further, we will also engage with communities and decision-makers, to ensure our science is usable and used, with broader impacts beyond the science community (as further described in Section 3.B.5). We note here that our capacity to conduct excellent ecosystem science and prediction research in support of NOAA also draws on strengths on the CU-Boulder side of our institute. CIRES hosts two centers of excellence in the production of usable science[240] serving society's needs, including the land-management needs of communities, states, regions, and Tribes: The WWA and the NCCASC (see: Institutional Capabilities and Composition, Section 3.C.).

Much of the work described in Themes 1-7 above can be applied to ecosystems science and prediction, including efforts to understand the potential impacts of climate changes on ecosystem health and productivity. For example, future nutrient projections from ocean models can be used to predict shifts in fish abundance off the U.S. West Coast.[341] Here, we describe past CIRES work and proposed CIESRDS work that directly assesses climate impacts on (1) marine and coastal ecosystems, and (2) terrestrial ecosystems.

3.B.8.b. CIESRDS Proposed Work for 2022-2027 and Beyond

3.B.8.b.1 Climate Impacts on Marine and Coastal Ecosystems

CIRES Background

CIRES and NOAA collaborators have successfully applied high-resolution atmosphere and ocean models to provide predictions of climate impacts on marine and coastal ecosystems at different lead times ranging from days to decades; work that directly supports management

decisions and adaptation planning (e.g., fisheries). CIRES and NOAA scientists have expertise in understanding how climate variability (e.g., modes of variability like ENSO and the Pacific Decadal Oscillation in the Pacific sector) can provide important sources of predictability for the physical drivers of marine ecosystems through local changes in ocean processes or remote influences via atmospheric teleconnections (e.g.,[176,342,343]). CIRES-led research has helped illuminate some of the drivers of marine heatwaves,[344,345] and predicting such conditions a few seasons in advance remains a key research goal, to serve marine resource planning. Other dynamic downscaling efforts simulate the present climate and the climate at the end of the century. This is very useful for understanding marine habitats along the coastline, for example, in the Gulf of Maine.[346,347]

CIRES has supported the assessment of marine mammal ecosystem health, as well, through the publication of the NSIDC Sea Ice Index and analysis of other Arctic environmental data. The National Marine Fisheries Service, for example, recently proposed a change in designated critical habitat for ringed seals and cited the Sea Ice Index. Other NSIDC data are also foundational to the Climate.gov Dashboard and NOAA's annual Arctic Report Card,[236] both of which reference polar bear and walrus habitat.

Future work of CIESRDS

CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Contribute to regional downscaling experiments with NOAA GFDL's state-of-the-art MOM6 and CMIP6 climate change scenarios.
- Use high-resolution reanalysis to document the relationship between SST and bottom temperatures in coastal marine ecosystems in the U.S. Atlantic and Pacific Coasts. We will study marine heatwaves and impacts in coastal ecosystems, ultimately using regional downscaling experiments.
- Extend the use of climate models, especially large ensembles of climate models, to further understand how climate variability and change affect the physical quantities that are critical for marine ecosystems, including extreme conditions. We will examine how local extremes are connected with the changing conditions in the global ocean.
- Improve understanding of the connections between physical and biogeochemical quantities in support of predictions and projections of those quantities.
- Use high-resolution global climate models and develop regional high-resolution models to assess the impact of climate variability and change at scales relevant to coastal communities and livelihoods.
- Develop empirical/statistical models, using the output from the high-resolution dynamical systems in specific regions of interest to perform efficient predictions of quantities needed by stakeholders. We will continue to improve the use of linear inverse modeling and provide modeled seasonal predictions of sea level via the NOAA Sea Level Rise web page.[348]
- Assess the relative role of local stochastic atmospheric forcing vs. large-scale climate influences to assess the degree of predictability of marine heatwaves, as well as their representation in climate models.

3.B.8.b.2 Climate Impacts on Terrestrial Ecosystems

CIRES Background

CIRES has led and conducted a great deal of research into regional and global climate drivers that are relevant to terrestrial ecosystem health. For example, the hydrometeorological observing network CIRES and NOAA colleagues established along the U.S. West Coast and hydrological model evaluation work we have done (see Section 3.B.4.), improves forecasts of extreme flooding events, low-flow periods for rivers, and snowpack levels—variables important to communities and ecosystems. Specific past ecological work includes work led by CIRES scientists assessing the future snow environment for denning wolverines in the Rockies, including in areas where reintroduction is being contemplated;[349] and work connecting low river flows and climate variability at decadal to multidecadal scales.[350] We have investigated how downscaling methods, e.g., NA-CORDEX, impact orographic precipitation and snowpack forecasts in U.S. West watersheds;[265] relevant for land and water managers balancing needs of ecosystems, communities, and agriculture.

CIRES drought researchers have also done important work at the intersection of climate and water availability, focusing on research that seeks to illuminate current and future impacts on human and ecological systems. For example, we led the development of EDDI, an experimental drought monitoring and early warning guidance tool that produces a measure of "the thirst" of the atmosphere.[178] EDDI can offer early warning of agricultural drought, hydrologic drought, and fire-weather—all important factors to ecosystems—by providing near-real-time information on the emergence or persistence of anomalous evaporative demand in a region. This team is now investigating the drivers of and predictability of quick-onset droughts called "flash droughts," which can be damaging to ecosystems, agriculture, and other human systems.[249]

Future Work of CIESRDS

CIESRDS scientists, in collaboration with NOAA and other colleagues, will:

- Produce and improve drought indices, such as EDDI, that help agricultural and land managers and other decision-makers anticipate future conditions.
- Evaluate and downscale regional model output over space and time to predict precipitation and snowpack and provide inputs for ecosystem assessments.
- Work to better understand flash drought as well as ecological drought, including definitions and parameters, and communicate upcoming conductions effectively, to ensure decision-makers have the information they need when they need it.
- Inform the ecosystem-focused work of the NCCASC on grasslands in the mid-continental United States. Needs for information from a recent grasslands synthesis include understanding how climate change and variability will impact grassland disturbance and restoration processes, woody encroachment, herbaceous invasives, grazing, water quality and quantity, animal species of conservation concern, and management alternatives in the face of changing climate.

3.C. Institutional Capabilities and Composition

With scientists, engineers, data analysis experts, developers, students, and other staff embedded in every NOAA Boulder laboratory and within 10 departments across the CU Boulder campus, CIRES has been well connected, and CIESRDS will be well-positioned to support NOAA needs and advance NOAA's mission.

CIRES has earned international and national recognition, including from NOAA, for our science and scientists who support the agency. For example:

- Six CIRES scientists, five of whom worked with NOAA groups, earned Presidential Early Career or PECASE awards during our last cooperative agreement: Rebecca Washenfelder (2012, now NOAA), David Noone (2012), Gijs de Boer (2016), Anne Perring (2017), Brian MacDonald (2019, now NOAA), and Andrew Rollings (2019, now NOAA).
- 11 CIRES scientists are Fellows of the American Geophysical Union or the American Meteorological Society, leading organizations that conduct NOAA-relevant science.
- CIRES scientists were key members and leaders of NOAA teams that earned Department of Commerce Gold Medals in 2015, 2016, 2017, and 2020; Silver Medals in 2016, 2019, and 2020; and Bronze Medals most years.
- CIRES scientists were critical to the science featured in 36 of the 100 stories NOAA Research News highlighted in the 12 months between September 2020 and September 2021.
- CIRES-led or CIRES-involved research and education successes are regularly featured in NOAA annual Science Reports, for example: A new sea-ice forecast system for the Arctic; Improvements in forecast models RAP and HRRR; FIREX-AQ, a climate and air quality research mission led by a CIRES scientist who obtained federal employment soon after the mission; improvements in heatwave forecasting; detection of increased emissions of CFC-11, a major ozone-depleting gas, in apparent violation of international agreements; a profile of CIRES' Lens on Climate Change program; development and improvements to EDDI; define and forecast drought conditions; and much, much more.

3.C.1. Specific Capabilities

3.C.1.a. Scientific, Service-Oriented Leadership

Our proposed new cooperative institute CIESRDS will benefit from years of NOAA engagement and collaboration by CIRES leadership, particularly the two Principal Investigators (PI)s Waleed Abdalati and Christine Wiedinmyer. Dr. Abdalati, an expert in climate-related cryospheric changes in the Arctic, has extensive experience in high levels of government, academia, and industry, and he has been recognized for his scientific achievements and leadership through various awards and appointments. He served as NASA chief scientist, and co-chaired a National Academies Study (NAS) that provided guidance to NOAA, NASA, and USGS on the next decade of investments in Earth Observation from Space. Dr. Abdalati also has extensive experience in communicating about science with people of all backgrounds, including during formal Congressional testimony and with various domestic and international political leaders. Dr. Abdalati will direct CIESRDS, and co-PI Dr. Wiedinmyer will serve as Associate Director for Science. Dr. Wiedinmyer is an atmospheric scientist and chemical engineer, with over 130 peer-reviewed publications and an ISI h-index of 49. Her work has long aligned with NOAA's science, and she has published collaboratively with NOAA Boulder colleagues in pollutant emissions, air quality, and the radiative impacts of smoke from wildfires. She has most recently served on the NAS Workshop Committee on Wildfires, Air Quality, and Health (2020). Dr. Wiedinmyer is a twice-elected Trustee of the University Corporation for Atmospheric Research (UCAR) (2018, 2021) and co-founder and a current member of the Board of Directors of the influential ESWN, a non-profit organization dedicated to increasing diversity across the geosciences. See Appendix 3 for PI CVs and current and pending support statements.

3.C.1.b. Artificial Intelligence

Many CIRES scientists currently embedded in NOAA's labs are leaders in innovating the use of AI methods, including ML, into a diverse array of NOAA research activities. At the most recent two NOAA workshops on Leveraging AI in Environmental Sciences, CIRES scientists presented plenary talks (2021), chaired sessions,[351,352] and presented papers[352] on diverse topics including deriving FRP from satellite imagery and implementing AI/ML techniques with new observations in data assimilation tools for terrestrial and space weather forecasting.

At the 2021 AGU Fall Meeting, CIRES scientists lead-authored or co-authored 19 presentations and posters that included data analysis and model applications that used AI, ML, or neural networks. These papers dealt with research topics that align with NOAA's priorities: for example, using neural network models for classifying sea ice types in the Chukchi Sea; applying a ML model to better predict fire intensity and emissions at times scales of hours-to-days; and using ML to normalize air quality parameters (ozone and PM2.5) to better describe long-term trends in those pollutants.

Outside of this AI work done in collaboration with NOAA, CIRES and CU Boulder have emerged as national leaders in the innovative use and analysis of big data, with a focus on Earth system data. CIRES' Earth Lab group, led by Geography professor and CIRES Fellow Jennifer Balch, is a national pioneer in big Earth data analysis, layering environmental, demographic, and other data in illuminating ways. Importantly, Earth Lab supports a vibrant and internationally recognized education program that reaches 200,000 users monthly through an Earth Data Science learning portal, and others through programs including the Earth Data Science Corps (in partnership with schools serving communities underrepresented in science, technology, engineering, and math), and an Earth Analytics Professional Certificate. Balch and Claire Montelione (CU Boulder College of Engineering) are collaborating to integrate ML more deeply into the environmental big data mix, to accelerate an open and diverse Earth data revolution as part of the CARE group.

Taking advantage of this AI expertise at CIRES and CU Boulder, CIESRDS will provide future opportunities for training and research activities that integrate transformative technologies such as AI into the key scientific activities that support NOAA.

3.C.1.c. Communications, Education, and DEI

CIRES' strong scientific reputation means our scientists and research are often sought after by journalists including from the *Washington Post*, major TV networks, the *Wall Street Journal*, *National Public Radio*, *USA Today*, *Smithsonian*, *WIRED*, *El Pais*, the *Guardian*, and many other outlets. CIESRDS communications professionals will work collaboratively with NOAA as discussed above, in Section 3.B.5. A CIESRDS communicator will be housed in the NOAA building and will meet weekly with communications experts from all NOAA Boulder laboratories.

Supported by experts from the university's Office of Government Relations and CIESRDS communicators, our scientists and leaders will speak regularly with decision-makers and elected officials, including testifying before state committees, the federal House Science, Space, and Technology Committee and the House Select Committee on the Climate Crisis, other Senate committees, and on demand as experts in various fields. We will participate in teleconferences,

learning sessions, and workshops hosted by both Democratic and Republican elected officials, bipartisan groups, and by non-partisan groups including CO-LABS, a business-led consortium that promotes, educates about, and connects federally funded research in Colorado. Importantly, CIESRDS, CU Boulder, NOAA, and other partner institutions will regularly offer communications training opportunities to our scientists.

The CIRES Education & Outreach team is nationally renowned for its expertise in curriculum development, student and teacher engagement, workforce and career development programs, research- and evaluation-based work, and scientific visualizations (the SOS program is part of this team). Our capabilities in this arena are unparalleled. Please find more information about this team's future work in the CIESRDS Education Section (3.D) and Scientific Outreach, Education and Diversity Section (3.B.5).

CIRES' Diversity and Inclusion Director is a national leader in efforts to improve representation and inclusion in Earth system science and data analytics. Because JEDI will be core values within CIESRDS, integrated into all we do as a research institute and federal partner, we describe CIESRDS' Diversity, Equity, and Inclusion program in the Business Plan (Section 3.E.) as well as in the Scientific Outreach, Education, and Diversity Section (3.B.5) above. JEDI will be foundational to every aspect of our new institute.

3.C.2. Composition

3.C.2.a. Established and Growing Expert Workforce

CIRES employs more than 400 people who work embedded in NOAA teams, comprising roughly half of the workforce of NOAA's renowned Earth System Research Laboratories (late 2021 figures). CIRES employs more than 70 people in NCEI (about two-thirds of NCEI's Boulder workforce); another 28 people in SWPC (about 40 percent of the workforce); and 6 in the WPC in Maryland. These experts will comprise the initial CIESRDS workforce.

Importantly, CIRES supports about 200 graduate and undergraduate students, annually. These early-career scientists enrich our research, often facilitate productive interactions between our campus-based and NOAA-based scientists and activities, and go on to obtain higher degrees as well as employment in NOAA, other federal agencies, academia, and industry. In the Education (3.D.) and Business Plan (3.E.) sections of this proposal, we provide more detailed information about existing and planned student and postdoctoral support, including initiatives to build and retain a diverse workforce. CIESRDS will take seriously its mission to train the world's next-generation researchers; our annual performance reviews, for example, will recognize mentorship.

CIRES has a long-standing reputation for collaborative work that crosses disciplinary boundaries, including the social sciences and other humanities; CIESRDS will build upon these connections. Grounded by the work of about 20 researchers at CU Boulder and CIRES who currently conduct social science and economics research, CIRES is launching the **Center for Social and Environmental Futures, C-SEF**, which will be led by environmental economist Matthew Burgess, a CIRES Fellow and assistant professor of Environmental Studies with a courtesy appointment in Economics. C-SEF will serve as a focal point for social/environmental/economic science at CU Boulder, aimed at investigating the fundamental

underlying drivers of, and assumptions about, society futures as they intersect with environmental goals and values. This unique research will bring together physical and social scientists, and we will facilitate interactions between NOAA-based CIESRDS researchers and C-SEF to identify potential pathways to support NOAA mission goals. This group's work will be well-aligned with several of CIESRDS' scientific foci, including Future Atmospheres; Climate Science and Prediction; and Ecosystems.

In addition, two of CIRES' centers focus directly on usable science to serve society's needs; these groups are also national leaders in co-produced science, which engages users from the beginning. The **WWA** is a NOAA-funded Regional Integrated Sciences and Assessments (RISA) program that conducts innovative research in partnership with decision-makers in the Intermountain West, helping them make the best use of science. WWA has been successful at engaging with stakeholders to ensure that CIRES and NOAA research informs the decisions of communities, states, utilities, and other entities by enabling people and businesses to manage climate impacts and build resilience, particularly to extremes.

The **NCCASC**, funded by the Department of Interior, is a collaboration with the USGS and five other partners to conduct innovative research, training, and data science to support ecosystem management in a 7-state region from Colorado to North Dakota. Ecosystem-related foci include habitat fragmentation, ecological drought, invasive species, and species restoration. The NCCASC also is a key focal point in CIRES for work with tribes on ecosystem management, and supports liaison work, training, and education focused on highlighting and expanding Indigenous capacity in ecosystem science, data science, and resource management.

3.C.2.b. A Unique, Collaborative Network

Finally, in Boulder, Colorado, CIESRDS will be part of a unique network of research organizations and scientists collaborating widely to develop and bring scientific and technical innovations to the world and to train next-generation environmental researchers. Our new institute will join an Earth system research and data science ecosystem that is unmatched in the country:

Colorado's Front Range hosts more than 30 federally funded research laboratories, creating one of the highest per-capita concentrations of experts in environmental science and technology in the nation. NOAA, NCAR, the National Renewable Energy Laboratory, the National Solar Observatory, the USGS, the National Ecological Observatory Network, and many other research labs are supported by the influential CO-LABS organization, which "promotes, educates, and connects" these federally-funded institutions with each other, the general public, decision-makers, and other audiences, fostering a rich and creative dialogue across these leaders in environmental science research.

CU Boulder is a world leader in research. In 2021, the Global Ranking of Academic Subjects[1] named CU Boulder as the # 1 university for both Earth Science (CalTech follows) and Atmospheric Science (the University of Washington follows). CU Boulder is first among public U.S. universities for NASA funding.[353] CIESRDS' home institution's top international ranking in geosciences and atmospheric sciences is in large part the result of the research conducted through the relationship between CIRES and NOAA and the opportunities for collaboration at all levels, from graduate students and postdocs to visiting sabbaticals.

CIRES NSIDC hosts a NASA Distributed Active Archive Center (DAAC). In 2018 NASA awarded the CIRES' NSIDC nearly $50M for five years to archive and disseminate data on the frozen parts of the world—including satellite and field measurements of changing ice conditions in Antarctica, Greenland, and the world's glaciers. NOAA created NSIDC in 1982, to archive data from agency programs and expand World Data Center holdings; NSIDC has served as a NASA DAAC since 1993.

CIRES' long-term collaborations support NOAA's needs. We collaborate with the Institute for Arctic and Alpine Research (INSTAAR) at CU Boulder, for example, to support NOAA's long-term atmospheric composition monitoring program. INSTAAR staff measure the stable isotopes of carbon dioxide and methane in weekly air samples NOAA collects from around the world, to better understand sources and sinks of the greenhouse gasses. It was a successful CIRES Innovative Research Project (see Education Section below, 3.D.), led by then-CIRES researchers Jocelyn Turnbull and John Miller, that led to the operationalization of this program.[354] CIRES researchers also work collaboratively with colleagues at CU Boulder's Laboratory for Atmospheric and Space Physics (LASP) on space weather research and technology, and with colleagues at NCAR on improving climate models, and much more.

CIRES scientists have become recognized leaders in the field of UxS applications in Earth system science, working collaboratively to develop and deploy UxS that have already provided ground-breaking perspectives on questions related to weather and climate. Through close collaboration with CU Boulder partners, including the Integrated Remote and In Situ Sensing Grand Challenge program, and NOAA laboratories including PSL, CSL, GML, and the National Severe Storms Laboratory (NSSL), we have used UxS to research turbulence and energy exchange (miniFlux), fire weather (Nighttime Fire Observations eXperiment (NightFox), high-altitude chemistry (High-altitude Operational Return Uncrewed System (HORUS); and mountain weather and hydrology (SPLASH). To address critical questions about weather and climate, we have worked in the Arctic (MOSAiC, Evaluation of Routine Atmospheric Sounding Measurements Using Unmanned Systems (ERASMUS), Profiling at Oliktok Point to Enhance YOPP Experiments (POPEYE), Stratified Ocean Dynamics of the Arctic (SODA), the tropics (ATOMIC, Elucidating the role of clouds-circulation coupling in climate (EUREC^{4}A), and in between (Wisconsin's Dynamic Influence of Shoreline Circulations on Ozone (WISCO-DISCO), Lower Atmospheric Profiling Studies at Elevation (LAPSE-RATE), and SPLASH). Deployments already in the planning phase include UxS research to track aerosol convection interactions (TRacking Aerosol Convection interactions ExpeRiment (TRACER), to investigate coastal dynamics and impacts on weather and air quality (Wisco-DISCO2), to study the atmospheric emissions and reactions from megacities to marine areas (AEROMMA) and research on the interplay between renewable energy technologies and the boundary layer (e.g., the American Wake Experiment and WFIP-3).

CIRES has an advanced **Integrated Instrument Development Facility** consisting of design, precision machine, electronics, and scientific glassblowing shops dedicated to the design and fabrication of scientific instrumentation. The facility specializes in complete instrument development, from concept to testing, and is able to assist CIESRDS and NOAA scientists at whatever level is needed. IIDF has three patents for methods of electroplating superconducting films that are of interest to companies developing quantum computers.

3.D. Education

CIRES is a world leader in scientific education, training, outreach, and engagement, and CIESRDS will develop and conduct programs and services that foster the development of world-class scientific leaders, researchers, innovators, educators, and opportunities. As CIESRDS, we will strengthen our collaborations with NOAA to cultivate a scientifically literate society served well by diverse scientists; those scientists will be conducting important environmental research that enables awareness of and resilience to environmental change and the education of a generation of planet stewards. Our purposes are shared: CIESRDS education work will align directly with NOAA's mission (To understand and predict changes in climate, weather, oceans, and coasts; *to share that knowledge and information with others;* and to conserve and manage coastal and marine ecosystems and resources).

In the Scientific Outreach, Education and Diversity Section above (3.B.5.), we describe CIESRDS proposed work as it aligns with the NOFO. Here, we provide more administrative and operational information on our educational programs and outreach work, which are core to CIRES and CU Boulder, a degree-granting institution with outstanding research capabilities in all areas of NOAA's mission.

3.D.1. Undergraduate, Graduate, and Postdoctoral Programs

CIRES encompasses 22 tenured or tenure-track faculty members who collectively teach an average of 2.5 graduate and undergraduate courses per year, or about 80 courses annually, serving hundreds of students in 10 departments. Table 3 lists the degree options in these departments, including more than a dozen bachelor's degrees, 10 Ph.D. types, 26 master's degrees, and 20 certifications, including professional. NOAA scientists and affiliates often guest lecture in CU Boulder courses taught by our faculty, and federal or federally-based scientists also occasionally *take* such courses, in the course of earning master's and Ph.D. degrees.

Table 3: CU Boulder Degree Options Available to CIESRDS Students

College	Department	Bachelor degrees offered (#/type)	Master's degrees offered (#/type)	# Ph.D. degrees	Certificates (#/type)
Engineering & Applied Sciences	Ann and H.J. Smead Aerospace Engineering Sciences	**2** BS in Aerospace Engineering Sciences, Concurrent BS/MS	**7** e.g., MS in Aerospace Engineering Sciences, Environmental Engineering, more	**1**	**5** e.g., Remote Sensing or Space Weather and Applications; more
	Civil, Environmental and Architectural Engineering	**3** BS in Civil Engineering; Environmental Engineering; Architectural Engineering	**5** e.g., Water Engineering and Management; Global Engineering; more	**1**	**3** e.g., Tunneling; Water Engineering & Management, more
Arts & Sciences	Chemistry	**1** BS	**2** MS with/out thesis	**1**	

	Department	Bachelor degrees offered (#/type)	Master's degrees offered (#/type)	# Ph.D. degrees	Certificates (#/type)
	Ecology and Evolutionary Biology	**2** BA; concurrent BA/ MA in Ecology and Evolutionary Biology	**3** MA I (with thesis); MA II (non-thesis); Bachelor's-Accelerated Master's (BAM)	**1**	
	Environmental Studies Program	**1** BA	**5** MEnv; MS; MS/MBA in collaboration with the Business School; MS/JD and PhD/JD in collaboration with the Law School	**1**	**1** Graduate Certificate Program in Environmental Justice
	Geological Sciences	**2** BA, Geology or Geophysics	**1** MS	**1**	**3** Geophysics, Hydrologic Sciences, and Remote Sensing
	Atmospheric and Ocean Sciences	**1** BA	**2** MS Non-Thesis Option; MS Thesis Option	**1**	**2** Atmospheric and Oceanic Sciences; Oceanography
	Economics	**1** BA	PhD students earn MA degree as they progress	**1**	
	Geography	**1** BA in Geography, four tracks: Physical Geography; Geographic Information Science; Human Geography; Environment-Society Relations	**1** MA	**1**	**6** e.g., Hydrolog. Sciences, Population Studies; Earth Data Analytics; Interdisciplinary Documentary Media Practices
	Molecular, Cellular & Developmental Biology	**1** BA		**1**	
Totals		**15**	**26**	**10**	**20**

In a typical year, CIESRDS will employ between 80 and 100 undergraduate students, and many of them are engaged directly in research opportunities CIESRDS provides. CIESRDS scientists will be able to participate in:

- The RECCS program, funded by NSF, which engages community college students in authentic research experiences, including with NOAA scientists;[355,356]
- The Earth Data Science Corps program, funded by NSF to boost diversity in big data fields, provides internship opportunities for students at Tribal colleges and other schools serving communities historically underrepresented in STEM.

CIESRDS scientists will mentor undergraduates through other programs including:

- NOAA's Hollings Scholarship program,
- NOAA's William M. Lapenta NOAA Student Internship Program,
- NOAA's Experiential Research and Training Opportunities (NERTO),
- NSF's Research Experiences for Undergraduates (REU),
- UNAVCO's Research Experiences in Solid Earth Sciences (RESES) (NSF), and
- UCAR's SOARS (NSF).

To highlight just one of these programs: The RECCS community college program, which began in 2014, aligns with NOAA's education[25] and diversity[26] goals. Fully funded by NSF for the last 7 years and with another 5 years of funding committed, RECCS brings students from backgrounds typically underrepresented in the geosciences to the CU Boulder and NOAA campuses, providing them with authentic research experiences, mentorship, and professional training. RECCS students are diverse along many dimensions, including first-generation college students, people of color, rural students, and veterans.

RECCS has served a total of 84 students and 23 of them worked with NOAA mentors and in NOAA labs. Many RECCS students (39% of whom are first-generation college students) have gone on to pursue graduate studies in STEM and many more are pursuing a 4-year degree in preparation for graduate school. The experience from RECCS contributes to the ongoing development of REU and REU-like programs in the geosciences across the nation through CIRES co-leadership of the NSF-funded GEO REU network. This network reaches nearly 400 internship program leaders and staff nationwide through an active listserv, shared resources, training and development opportunities, and cultivating a supportive community of practice.

Inspiring Early-Career Scientists

Before starting the RECCS program in the summer of 2018, Prudence Crawmer already wore many hats: "small business owner," "massage therapist," "student"—and now she can add "scientist" and "international award winner" to that list. Crawmer worked with RECCS mentor Rick Saltus (CIRES/NCEI) on a citizen science app called CrowdMag, which collects geomagnetic data from smartphones to identify magnetic field disturbances that affect navigation. Her work won a scientific poster contest, sending her to the largest Earth science conference in the world, the American Geophysical Union Fall Meeting. "I was exposed to research career paths I never knew existed," said Crawmer, now an undergraduate at the University of Colorado, Colorado Springs, majoring in

Environmental Studies and Geography with a GIS Certificate. “Pru's work took the app in a whole new direction,” said Saltus. “I learned just as much from her as she did from me.” Photo by Rick Saltus/CIRES/NOAA.

CIRES supports 80-120 graduate students annually and is a leader in graduate education at CU Boulder, because of the prestige of our scientists[1] and the support we provide to our students. These students earn their master’s and Ph.D. degrees from departments at CU Boulder, and they are sometimes co-advised by NOAA-based scientists. CIRES graduates can be found in the halls of NOAA buildings across the country; in academic institutions across the world; in private industry; and in the fronts of classrooms—carrying forward the NOAA mission that is at the root of their training.

Our proposed CIESRDS work supporting graduate students, postdocs, and other early-career researchers is detailed elsewhere in this proposal, in Scientific Outreach, Education and Diversity Section above (3.B.5), and in the Business Plan below (3.E.). As noted there, we will devote considerable resources to supporting early-career scientists, offering frequent professional trainings, supporting a Graduate Association (for graduate students and postdocs), and encouraging engagement through our education, outreach, and communications programs. We will run a prestigious postdoctoral and sabbatical visiting fellowship program (3.B.5) and will provide the opportunity for Innovative Research Project seed grants to support highly inventive, multidisciplinary work. CIESRDS will be a magnet for early-career polar researchers and will support them at NOAA and on campus, for example, with the our NSF-funded Polar Early Career Scientist Community Office.

3.D.2. Learners of All Ages

Our education experts work across the spectrum of geosciences and environmental education, to inspire learners of all ages and widely disseminate CU Boulder and NOAA science; CIESRDS’ work in this arena will include: professional development for hundreds of teachers each year, cutting-edge digital learning resources (virtual experiences, story maps, dome-based planetarium shows, 360 videos, Massive Open Online Courses, GIS system development), innovative curricula that use research-backed pedagogical approaches to translate authentic scientific data and information into learning opportunities (e.g., data puzzles, scenario games, curriculum units), engaging student programs, working with education leaders to support education efforts nation-wide, and career and workforce development.

Our Education and Outreach program will support each of the objectives and strategies outlined in the 2021-2040 NOAA Education Strategic Plan, and the Education and Outreach Program has grown considerably in the last 5 years due primarily to successful grant writing. The team now includes 22 curriculum developers, scientists, educators, communications experts, a museologist, graphic designer, cognitive psychologist, evaluators, and others who work together to broaden the impact of NOAA and other science and make science topics accessible to a wide audience. The team’s work is scholarly in its own right, frequently published in journal articles. CIRES has invested directly in this team, supporting an infrastructure that enables its success; CIESRDS will provide education and outreach support for some of NOAA’s flagship programs (eg, CLEAN and SOS, described in 3.B.5.), and our Education and Outreach program will conduct

externally funded work closely aligned with NOAA's and CIESRDS' Earth system and data science focus.

Three other examples describe the types of work NOAA can expect from our Education and Outreach program: (1) HEART Force, funded by NOAA's Environmental Literacy Program, engages youth and teachers to raise awareness of natural hazards and inspire action for resilience in rural Colorado communities; (2) QGreenland, funded by NSF, is a free and open-source GIS mapping tool that supports interdisciplinary Greenland-focused research, teaching, decision making, and collaboration; and (3) We Are Water, funded by NSF, is a partnership with libraries in the Four Corners Region to bring a traveling exhibit and programming about the importance of water to rural, Latinx, and Indigenous communities in the Southwest.

Our Education and Outreach experts will promote and strengthen scientific and environmental literacy by engaging communities in project work, inspiring and preparing the next generation of STEM researchers for careers in Earth and environmental sciences towards building a sustainable future. Please see the Scientific Outreach, Education, and Diversity Section (3.B.5.). for more information on the proposed work.

3.D.3. Public Engagement

CIRES has long collaborated closely with NOAA and CU Boulder to engage the general public in scientific research, grounded by a responsibility to the taxpayers who fund most of our work. CIESRDS will work closely with local NOAA leadership to ensure that our activities support agency priorities. Proposed projects in this area are detailed above, in the Scientific Outreach, Education and Diversity Section (3.B.5.). Administratively, we work closely with NOAA in outreach work: A CIESRDS communicator will lead the production of the NOAA Boulder Briefing, for example, and CIESRDS education and outreach experts will be integral to the NOAA Boulder Outreach Coordinating Committee, which facilitates close collaboration and integration of our work. These experts will serve as CIESRDS' public engagement specialists.

3.E. Business Plan

3.E.1. Governance and Leadership

CIESRDS will be a research entity within CU Boulder, governed by the laws of the Regents of the University of Colorado and by the administrative policies and regulations of the CU system and the Boulder campus, as stated in our bylaws. To the fullest possible extent, CIESRDS will accommodate the operational practices of its external research partners, including NOAA, as long as this accommodation is consistent with our governance. If funded, CIESRDS will be the largest component of CIRES, representing our new cooperative relationship with NOAA.

Research institutes at CU Boulder are part of the Research & Innovation Office (RIO), and CIESRDS activities will be overseen by the Vice Chancellor for Research & Innovation. The CIESRDS Director will report to this Vice Chancellor and will be responsible for all aspects of the operation of CIESRDS as a cooperative institute with NOAA. In accordance with the Cooperative Institute (CI) handbook, the CIESRDS Director will be responsible for oversight of all NOAA-funded activities associated with the institute, including proposals, reports, and

reviews. The Director will be a CU Boulder faculty member in good standing and will serve for one or more terms of four years.

The **CIESRDS Director** and administrative staff will have extensive experience supporting our research enterprise with excellent administrative services, ensuring compliance with relevant regulations and policies. We propose to continue working closely with NOAA leaders and administrative experts to ensure alignment of practices and to quickly address problems. Enhanced communication and collaboration between CIESRDS and NOAA is described in more detail in the sections below, but will include: Participation in the NOAA CI Directors Executive Committee, which Dr. Abdalati has led for 8 years; participation or leadership in the national CI Directors and Administrators annual meetings; phone, email and other online communications; regular meetings among scientific and administrative leaders in Boulder, Colorado; and in-person staffing to support our researchers in Boulder's NOAA DSRC.

Our **Council of Fellows** will advise the CIESRDS Director on major policy and scientific direction, meeting monthly during the academic year or when convened by the Director. The non-Federal members of the Council of Fellows conduct a search when a new Director is needed and recommend a nominee to the Vice Chancellor for Research and Innovation, for appointment.

CIESRDS will support other committees to advise the Director. For example:

- The **Executive Advisory Board** ("Executive Committee") will consist of the CIESRDS Director, Associate Director, Associate Director for Science (ADS), selected Fellows, and one representative elected by our employee organization, described below). The Executive Committee meets as determined by the Director, typically monthly during the academic year. The Executive Committee advises the Director on matters to be brought to the Council of Fellows and in developing CIRES and CIESRDS strategic guidance.
- The **Senior Management Team** (SMT) will be an advisory group of administrative leaders, selected by the Director. Members of this group are responsible for tracking and understanding university, NOAA, and other policies that impact CIESRDS; discussing and addressing issues within and outside of the institute; executing the business functions of the institute, and implementing change. This team will meet weekly or at the Director's will, and members of this team will communicate and coordinate regularly with NOAA colleagues. This team will also be responsible for sending monthly email and newsletters and for planning/hosting regular Town Halls for all employees, to build bridges between various parts of the enterprise and to communicate essential administrative information.
- CIESRDS leadership will be responsive to the **Members' Council,** an organization of employees. The Members' Council represents and articulates the interests and concerns of CIESRDS and other CIRES employees ("members"). The Members' Council will meet monthly; have direct access to the Director and ADS, as needed; and will send representatives to meetings of the Fellows meetings and the Executive Committee.

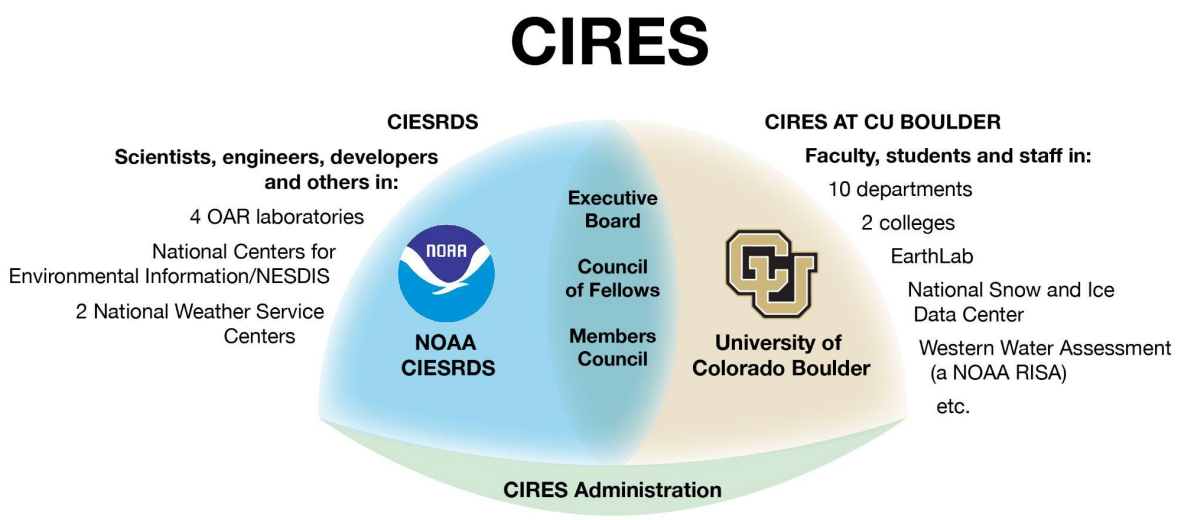


Figure 1: CIRES Composition. If the CIESRDS is awarded, the new cooperative institute will be at the core of CIRES, the broader institute; CIRES also includes CU Boulder-based research that is complementary and well-aligned with NOAA's mission.

3.E.2. Administrative Services, Including Fiscal & Human Resource Management

Our organization is viewed as a highly desirable place to work on the university campus, given its high-impact scientific mission and people-first approach. CIRES employs about 830 people, including undergraduate and graduate students. About half of these CIRES researchers work in the DSRC collaborating closely with federal scientists in the NOAA laboratories located there—these roughly 415 experts will comprise the initial CIESRDS workforce.

We will employ a professional administrative staff of sufficient size to support CIESRDS scientists in their various roles and to meet the needs of the cooperative institute. The administrative staff will include experts in finance, human resources (HR), D&I, communications, education and outreach, information technology, facilities, event planning, and general administrative support (Figure 3). The administrative team will continue to ensure all employees—researchers, faculty, administrators, and students—receive the support necessary to fully engage in their work and progress in their careers. Our administrative strength and success will be ensured by the exceptionally generous indirect cost recovery share that will be provided to us by the university for this cooperative agreement.

Human Resource Management

Experienced HR staff will administer all aspects of CIESRDS hiring, employment (including annual performance reviews), training and professional development, payroll, compensation, international employee support, and benefits. The current team has an excellent track record of recruiting and retaining exceptional researchers, and contributing to the development of NOAA's federal workforce (e.g., 52 CIRES employees obtained federal positions in NOAA during the last 10 years).

Paving the way for national recognition, federal employment

NOAA atmospheric chemist Rebecca Washenfelder began her research career at CIRES in 2007, where she developed a new instrument that uses light to measure trace pollutants in the atmosphere. She deployed new instruments during several field campaigns, including the 2010 CalNex campaign in Los Angeles and the 2013 SOAS campaign in Alabama, to study the sources and composition of aerosols that can impact both air quality and climate. In 2012, Washenfelder earned prestigious national recognition from the White House: the Presidential Early Career Award for Scientists and Engineers. In 2017, she accepted a research position in NOAA's Chemical Sciences Laboratory, where she continues to develop instruments (including for the FIREX-AQ campaign) and is actively involved in public education and outreach. 2010 photo by Bill Dube/CIRES/NOAA.

Our HR experts will onboard all new employees, to introduce them to CIESRDS, CIRES and university policies, procedures, benefits, and other relevant details, including expectations of those working in the NOAA laboratories. CIESRDS employees will be hired and supervised by CIESRDS employees, and individuals and teams will also benefit from the support of a federal science advisor.

Our HR team will work closely with university HR to offer all CIESRDS employees high-caliber and relevant professional and personal development opportunities, mental health support resources, and employee recognition programs. Regular training opportunities will include topics such as: Inclusive hiring and recruiting practices; supervisor expectations; on/off-boarding; and skills development in areas of leadership, project management, communications, and more. HR will be committed to ensuring an inclusive approach to its work and related guidance. This includes extending training opportunities to our federal colleagues as well, whenever possible and permitted. HR partners regularly with the Director of Diversity and Inclusion, working with the campus Office of Institutional Equity and Compliance to monitor workforce demographics and hiring process metrics, to track trends towards a more diverse workforce. CIESRDS' proposed professional development work is further described above in the Scientific Outreach, Education, and Diversity Section (3.B.5.).

Diversity and Inclusion

JEDI are values that CIRES, CU Boulder and NOAA are working to integrate into everything we do. CIRES has invested in DEI personnel and programming since 2017, in support of NOAA DEI Strategic Goals. The CIESRDS DEI Program will coordinate with NOAA and with campus partners to develop an inclusive workplace culture, recruit and retain a diverse workforce, and partner with organizations that serve underrepresented and minoritized groups. Our successes and plans include the following (and please note that specific proposed DEI-related projects are further described above in Scientific Outreach, Education and Diversity Section above (3.B.5.):

- Administrative actions taken in response to an institutional workplace culture survey resulted in statistically significant improvements to the workplace culture within one year,

such as decreased instances of incivility. CIESRDS will track workplace culture at regular intervals to assess state-of-the-culture and to plan annual actions in response.
- Our HR team is currently working to identify and rectify any identity-based compensation disparities as part of our response to the Colorado Equal Pay Act for example through an institute-wide compensation analysis. CIESRDS will continue to develop fair and competitive salaries for CIESRDS staff that comply with state and federal laws.
- CIESRDS will systematically scale up inclusive recruiting, search and hiring practices, and assessment of workforce demographics and hiring metrics (in partnership with CU Boulder Equal Employment Opportunity (EEO).
- CIESRDS will support programs such as the members mentoring program (including inclusive mentoring training), a graduate student and postdoc association, a DEI Community of Practice, and will promote inter-Institute affinity groups.
- CIESRDS will expand upon existing and build new relationships with organizations that support underrepresented and minoritized students and scientists, such as the NOAA CSCs, and professional societies that promote DEI in the sciences.

Fiscal Management

Our Finance office provides comprehensive day-to-day management of the institute's sponsored and non-sponsored funding and provides high-quality pre and post-award administration support services. CIESRDS finance staff will work in partnership with CU Boulder's Office of Contracts and Grants, the Campus Controller's Office, the Research & Innovation Office, Export Control, CU Legal Counsel, and others to ensure compliance with all applicable federal, state, and funding agency regulations, and university policies, as well as award terms and conditions. Finance staff will monitor all expenditures to ensure they are compliant, reasonable, allowable, and allocable to the project. The Campus Controller's Office generates and submits required periodic financial reports and Finance will monitor this process as well as technical report submissions by PIs. Finance staff will administer award close-out procedures to ensure all University and funding agency requirements are met. Finance staff will work closely with the Campus Controller's Office in all aspects of fiscal management and provide additional support services to PIs, such as tracking known encumbrances and monitoring spending rates using a customized reporting tool developed in-house. CU Boulder has a centralized Project Management Office that provides resources, training and access to Project Management Professional certification and will assist in meeting funding agency expectations for successful award management. Dedicated staff will assist with university compliance reporting, licenses, and permits for fieldwork, disclosure agreements, and analysis necessary to address export control concerns related to travel, shipping, visitors, and deemed exports. Finance will have dedicated travel liaisons who review and approve all business travel. Staff will regularly attend training to maintain expertise specific to sponsored award administration; CIESRDS will ensure successful, compliant, fiscally responsible management of the NOAA cooperative agreement.

Administrative Support Structure at NOAA Facilities

Administrative experts will regularly staff four physical offices in NOAA's DSRC to provide administrative support for CIESRDS employees working in the building and ensure robust communication and collaboration between CIESRDS and NOAA. These offices are for:

1. A liaison, who will have extensive knowledge of CIESRDS and campus people and policies. This person will onboard NOAA-based CIESRDS employees and support day-to-day administrative tasks such as HR and travel support.
2. A rotation of leaders, which may include the Directors of Communications, D&I, Education and Outreach, Finance, HR, and IT and Operations; the CIESRDS Director; or their designees. These leaders will support CIESRDS employees and coordinate with NOAA colleagues serving in similar roles.
3. A sustained presence of the CIESRDS Associate Director of Science, who will supervise and/or mentor CIESRDS scientists, who will identify scientific opportunities, and who will engage in regular, ongoing communications with NOAA leadership in Boulder to develop scientific workplans and ensure CIESRDS employees are working collaboratively on projects supported by the agency.
4. A science communicator, who will produce and support the production of internal and external communication products about CIESRDS and NOAA scientific discoveries, successes, innovations, and people.

CIESRDS will also have a scientific Lead position in each of the NOAA laboratories or centers at the DSRC. These Leads will be supervised directly by the ADS, be at the top of the supervisory tree in their unit, and will be a primary point of contact between their laboratory or center and CIESRDS leadership and administration. This will increase communications and collaborations across the organizations.

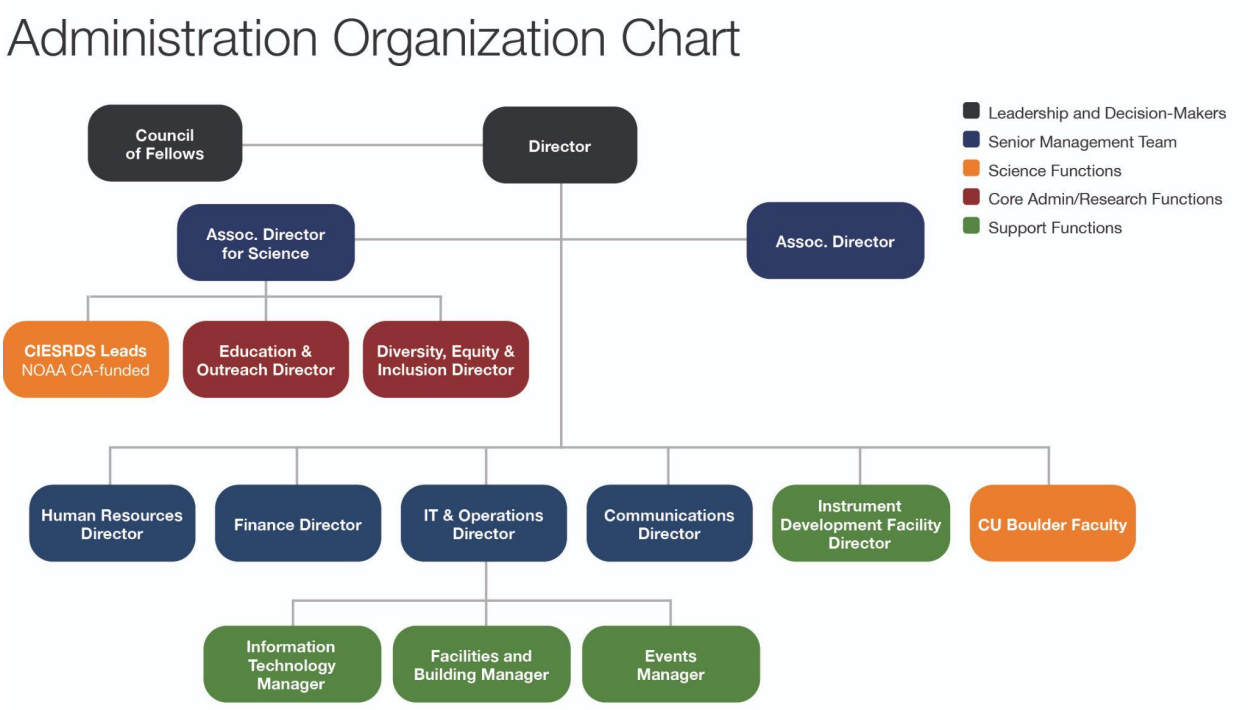


Figure 2: Administration Organizational Chart. This sketch shows the administrative organization of our institute, with, for example, the Associate Director of Science supervising CIESRDS Leads. The CIESRDS Director is ultimately responsible for administering the entire institute.

3.E.3. Operations

Accountability and Project Choice

CIESRDS, as a unit of the University of Colorado, will be accountable to all its stakeholders, including the university system and campus, sponsoring agencies, its PIs and employees, the international scientific community, and the public at large.

We will ensure our cooperative agreement-funded work aligns with NOAA, CIRES, and CU Boulder strategic objectives and policies. Scientific priorities will be set in collaboration with NOAA partners and aligned through the annual CIESRDS workplan. To ensure accountability to that plan, CIESRDS will report annually to NOAA through an annual report, delivered on deadline and in the format required by the CI handbook or other guidance.

Initially, our scientific and support activities will be divided into the projects associated with the Research Themes described in Section 3.B. Each project will be developed in collaboration with federal partners and will align with the goals and themes of the strategic plans of CIESRDS, NOAA, and other supporting agencies. CIESRDS scientists will be highly integrated within the NOAA centers and labs in Boulder, and this collaborative setting enables the identification and development of new projects and research directions. Moreover, CIESRDS scientists will be agile and responsive, so external events requiring rapid response may drive new projects that align with the NOAA mission. Relevant CIESRDS and NOAA scientists and managers will contribute to project definition, scope, goals, and deliverables, ensuring that projects contribute to NOAA goals and objectives and make appropriate use of CIESRDS expertise and resources. NOAA sponsors will not have supervisory, budgetary or spending authority over CIESRDS personnel or projects, but will have responsibility to coordinate scientific efforts in support of NOAA's objectives.

CIESRDS scientists may also pursue other funding opportunities—when agreed to by NOAA Lab and Center Directors—that are aligned with their NOAA research goals, supplementing and amplifying the work supported by the cooperative agreement.

CIESRDS will host regular retreats, an annual science symposium, and will create other opportunities to bring diverse scientists together to identify new research opportunities and pursue opportunities collaboratively. These gatherings will include researchers from the campus side of CIRES as well as the CIESRDS and NOAA side and are meant to inspire innovation and creativity in research. We will support an annual Distinguished Lecture Series, with invitees selected by a committee of Fellows; an Outstanding Performance Awards program run by our members council; and ~5-8 Innovative Research Projects every year, through a competitive process.

Strategic Planning

If funded, CIESRDS will develop a strategic plan in 2023, aligned with the CIESRDS goals described in Section 3.A, NOAA's guidance documents, CU Boulder's strategic imperatives, and the new CIRES strategic plan (Appendix 2). CIRES' plan is the result of a year-long re-visioning process and already includes a strong focus on engagement with and service to NOAA. Ultimately, the CIESRDS Director will have primary responsibility

for setting the vision of the institute and developing programs. The Director will do so with guidance from a strategic planning committee and senior staff who are tracking priorities of NOAA and CU Boulder.

3.F. Performance Measures

We propose performance evaluation on multiple timescales and levels of organization. If this proposal is accepted, CIESRDS will finalize a set of acceptable performance measures, which will include:

- **Individual** annual performance reviews, including assessment of: scientific achievements, publications, software and dataset development, technology transfer, honors and awards, JEDI work, education and outreach service, and more.
- **Project** performance reports, conducted annually through Research Performance Progress Report (RPPR) and NOAA communication required in each group, including:
  - annual re-alignment of our workplan with NOAA leadership, and
  - additional reporting as required by NOAA for specific projects.
- **Institutional** performance reviews:
  - The Boulder campus Academic Review and Planning Advisory Committee (ARPAC) reviews all academic units every 7 years. Our next review will be in 2025.
  - NOAA reviews:
    - CIESRDS will be reviewed by NOAA four years into its new cooperative agreement with the agency.
    - NOAA laboratory reviews consistently involve presentations by CIESRDS scientists embedded in those groups.
- **Other metrics** recommended in NOAA's CI21 study,[357] including publications, products transitioned into operations, leveraged funding, number of Ph.D. and Master's degrees awarded, number of employees who attain NOAA employment, media reporting on CIESRDS science, and descriptions of public outreach.

4. CIESRDS Data Management Plan

Data management and discovery are critical to the mission of NOAA and CIESRDS as leading scientific entities. To maintain scientific integrity and meet all requirements set forth by NOAA's Data and Publication Sharing Directives, CIESRDS will follow data stewardship practices that ensure FAIR principles: that data are Findable, Accessible, Interoperable, and Reusable for future generations. When working with Indigenous partners or data that includes Indigenous people we will follow the Collective Benefit, Authority of Control, Responsibility, and Ethics (CARE) Data management principles allowing our institute to engage with Indigenous Peoples rights and interests. Data managers at CIESRDS will stay up-to-date on community standards in order to follow the constantly evolving best practices in the field. As an organization composed primarily of research scientists, CIESRDS will be committed to ensuring environmental data are available to future generations. As data volumes increase exponentially, data stewardship is essential to ensure NOAA environmental measurements remain open source, easily discoverable, accessible, and well documented.

CIESRDS will maintain the most current data stewardship requirements and will dynamically adjust to a changing world of data resources and storage mechanisms to make NOAA data accessible and discoverable. Our data scientists within NOAA labs and centers will adhere to guidelines outlined in NOAA's Data and Publication Sharing Directives on data management, access, documentation, and citation identifiers.

Data management plans will be implemented and followed throughout project lifecycles. These comprehensive plans will be stored in the NOAA Data Management Plan repository. In terms of access, CIESRDS data managers will ensure the data are available in machine-readable, open-standard digital formats such as netCDF. When appropriate, data managers will also release data in discipline-specific, machine-readable formats such as Flexible Image Transport System (FITS) files for solar images, JavaScript Object Notation (JSON), and Comma Separated Values (CSV). This practice will increase data utilization. CIESRDS employees will write data monitoring tools to ensure consistent delivery of data delivered from sources such as satellites, ocean buoys, and other data-collecting devices. Dataset documentation will follow the ISO 19115-2 Geographic Metadata Standard. CIESRDS data managers will use the assessment rubric to ensure metadata are complete, and metadata will then be harvested and presented via web-accessible folders (WAFs). This will facilitate data discovery by making datasets available through the NOAA Data Catalog and OneStop. Finally, CIESRDS employees will follow NOAA data citation guidelines by minting DOIs that follow the ISO 263224 standard for data citations.

CIESRDS researchers will be required annually to submit to NOAA's Institutional Repository any papers or datasets supported to any degree by the Cooperative Agreement. Data will be provided to the appropriate data repository in a timely manner, generally within two years of acquisition or processing, unless extenuating circumstances delay availability.

CIESRDS will be well-positioned to meet the objectives of the NOAA Cloud Strategic plan. CIRES researchers already provide the expertise and development infrastructure to enable cloud-based data tools and training data. In fact, CIRES employees were among the earliest to pilot storing NOAA data in the cloud via AWS. In 2012, the CIRES geomagnetism group started providing—on the Google Cloud—a real-time forecasting service[358] for the prompt-penetration variations in the equatorial-eastward electric field. This service is currently used by SWPC's Coupled Thermosphere Ionosphere Plasmasphere Electrodynamics Model (CTIPe) real-time modeling[359] and by numerous researchers to account for the prompt-penetration effect. In 2015, the group developed a cloud-based model to provide a real-time magnetic field component for the NCEI's HDGM.[360] In 2018, CIRES Researchers in NCEI started a new service to forecast the Dst indices using ML modeling of solar-wind data. Additionally, the geomagnetism group provides[361] for the WMM on the cloud to serve the public in the event of the NCEI web servers going offline for any period of time. This experience has positioned CIRES well for the future. Utilizing AWS, Google Cloud, and Microsoft Azure agreements, as well as in-house cloud experts, CIESRDS will be able to tackle the problems related to cloud services.

CIESRDS teams will be national leaders in cloud computing with environmental data. Such work is critical already in several groups, including NCEI, in particular, and we expect continued growth in this area of environmental science. With a nationally recognized center of excellence

in this field, Earth Lab, we are well-positioned to continue innovations in many aspects, from developing software to applying ML.

CIESRDS will be home to many data professionals who will analyze, prepare, and make scientific data available on a daily basis. Our team members in NCEI will work diligently to prepare data and maintain current datasets that are human- and machine-readable, accessible via multiple avenues such as NOAA Data Catalog and OneStop, and provide meta-data that make the data reusable and accessible to the scientific community and public.

Our campus expertise will also benefit CIESRDS. CIRES employees at the NSIDC are data professionals who have served at the forefront of cryospheric data management practices for many decades. NSIDC is a Core Trust Seal accredited repository that follows the same FAIR data principles as our NOAA data science teams. NSIDC experts stay current on these principles by participating in and understanding the evolving standards of professional data communities. NSIDC uses modern data management practices and systems to operate sophisticated scientific data search applications that provide discovery and access to a diverse data catalog.

By adhering to FAIR data principles, meeting all requirements set forth by NOAA's Data and Publication Sharing Directives, and maintaining a professional workforce in the data management arena, CIESRDS will be at the forefront of making data accessible, available, and usable for current and future generations.

5. Budget Justification

Attached separately, please see Budget Narrative document.

6. Appendices

Appendix 1: References

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Appendix 2: CIRES Strategic Plan: Mission, Vision, and Strategic Imperatives

CIRES began a process of revising our Strategic Plan in 2021, and this process is ongoing by design: We see our strategic plan as a living document that will be revised continually. Below are the current Mission, Vision, and Strategic Imperatives.

CIRES Mission

To conduct innovative research that advances our understanding of the global, regional, and local environments and the human relationship with those environments, for the benefit of society.

Vision Statement

CIRES is an international leader in conducting cross-cutting environmental research of the highest quality while bridging fundamental science and service to society. We build leaders, scientists, communicators, and teams dedicated to developing sound and trusted information to address environmental challenges. We embrace a positive and inclusive culture, recognizing that CIRES thrives when our people do.

Strategic Imperatives

1. Advance our robust and creative research capabilities to further knowledge in the environmental sciences and the realization of its benefits.
    a. Strengthen and opportunistically enhance existing research, outreach, and engagement programs to keep CIRES at the forefront of scientific excellence and impact.
        i. Support the continued excellence and development of existing research, outreach, and engagement programs
        ii. Be responsive to and support researchers and research groups who identify and want to capitalize on opportunities for innovative new research directions.
        iii. Create mechanisms that encourage graduate students to catalyze research collaborations across CIRES groups in both CU and NOAA.
    b. Collectively identify, prioritize and implement new initiatives, opportunities, and research directions.
        i. Identify new initiatives through diverse mechanisms that solicit input from all of CIRES.
        ii. Prioritize new initiatives through regular retreats to assess trends and resources as an institute. Define a protocol for identifying pivot points given trends in metrics. Establish a decision and implementation mechanism.
2. Strategically link research groups and improve the mobility of our people and ideas to enhance innovation and interdisciplinarity across CIRES.
    a. Get to know one another
        i. Campus and NOAA Seminar Series
        ii. Tours of research teams / students / postdocs of NOAA labs
        iii. Create mechanisms to make it easier for CIRES@NOAA and NOAA scientists to guest lecture and help with classes on campus
    b. Link people who work on similar themes

        i. Expert-to-expert meetings on specific topics with contributions from across CIRES
        ii. Panel discussions on different themes with experts from across CIRES (with themes proposed by CIRES members)
    c. Establish new cross-disciplinary relationships focused on exploratory themes
        i. Retreats to bring people together, cross-disciplinary themes
        ii. Fund IRP, GSRA, VFP for cross-CIRES research activities
        iii. Designate a dedicated person to facilitate and coordinate cross-disciplinary activities
    d. Foster innovation through collaboration
        i. Define innovation for different job types (staff, researchers, students, faculty) and areas of improvement (leadership, diversity, inclusivity, outreach).
        ii. Develop programs and activities that encourage people to communicate who don't typically interact with each other (students, fellows, early-career researchers, staff, centers, etc.)
        iii. Identify meeting space outside of secure areas
        iv. Provide opportunities for shared supervision of scientific staff and students
3. Advance justice, equity, and inclusion through robust workforce development programs to promote excellence and diversity while inspiring engagement, innovation, collaboration, and leadership at all levels.
    a. Provide full support to the CIRES DEI Strategic Plan, gather data that informs ongoing employee engagement initiatives.
        i. Assess employee satisfaction on a regular basis and encourage participation in campus culture surveys.
        ii. Track personnel complaints and employee relations issues.
        iii. Evaluate retention efforts and programs for existing employees, including monitoring turnover rates, incentivizing completion of exit interview surveys, performing stay interviews.
        iv. Increase engagement levels through CIRES-wide events such as town halls and cross-disciplinary workshops.
    b. Build leadership and management training that creates opportunities for professional growth and monitor participation and outcomes.
        i. Implement CU HR training as appropriate.
        ii. Develop and implement new, evidence-based, CIRES-specific trainings.
        iii. Promote trainings and related CIRES professional development funding.
        iv. Collect feedback via the ASA process to inform professional development programming.
    c. Mentoring: Extend existing programs and implement a graduate student mentoring program.
        i. Institute discussions with graduate students to determine nature and organization of an effective mentoring program for that group.
        ii. Implement graduate student mentoring program.
        iii. Identify other groups in CIRES that would benefit and are not covered under current programs.

4. Enhance the impact, accessibility, and reach of our science to the broader scientific community, NOAA, educators and students, policymakers, and the general public.
    a. Collaborate widely on outreach and communications efforts within and beyond CU Boulder and NOAA to promote scientific literacy and CIRES science:
        i. Support “broader impacts” work in new science proposals and connect researchers to existing opportunities to have broader impact.
        ii. Regularly connect policymakers, journalists, and the public who have questions with scientists who may have answers
        iii. Enhance strategic communication on specific, focused topics through hiring, making connections, and expanding graphics and data visualization capabilities.
        iv. Collaborate with other departments and student groups to make science-based content more accessible to broader audiences
    b. Expand participation and skill in outreach and communications:
        i. Work toward a culture that values authentic research-related communications and outreach, including in performance evaluations
        ii. Build more skillful science communicators by supporting, enabling, and training scientists and students who want to do outreach or communications to develop their skills.

Appendix 3: PI Current and Pending Support Statements and Curricula Vitae

Current and Pending Support: Waleed Abdalati
Current
Project title: Cooperative Institute for Research in Environmental Sciences (CIRES)
Supporting agency with grant number: NOAA Award NA17OAR4320101
Investigator months per year: 6 months/year
Dollar value: $334,000,000
Duration: 9/2017 – 08/2022

Pending
Project title: Cooperative Institute for Earth System Research and Data Science
Supporting agency with grant number: NOAA, Proposal to NOAA-OAR-CIPO-2022-2007108
Investigator months per year: 4.8 months/year
Dollar value: $565,800,000
Duration: 9/2022 - 8/2027

Current and Pending Support: Christine Wiedinmyer
Current
Project title: Multi-scale chemical forecasting and analysis for FIREChem
Supporting agency with grant number: NASA Award 80NSSC18K0681
Investigator months per year: Yr 1: 1.2 mos; Yr 2: 0.8 mos; Yr 3: 0.8 mos
Dollar value: $525,000
Duration: 03/2018 – 03/2022
Note: Unfunded collaborator

Project title: AON: Atmospheric Tracers for Arctic Wildfires, Air Pollution, Atmospheric Chemistry, and Climate Change at GEOSummit, Greenland
Supporting agency with grant number: NSF Award OPP 1822406
Investigator months per year: 0.25 months/year
Dollar value: $929,628
Duration: 10/2018 – 01/2022

Project title: Arctic Community Resilience to Boreal Environmental change: Assessing Risks from fire and disease (ACRoBEAR)
Supporting agency with grant number: Belmont Forum Award
Investigator months per year: 0.01 months/year
Dollar value: $2,133,000
Duration: 01/2020 – 12/2023
Note: Unfunded collaborator

Project Title: Cooperative Institute for Research in Environmental Sciences (CIRES)
Supporting agency with grant number: NOAA Award NA17OAR4320101
Investigator months per year: 10.8 months/year

Dollar value: $334,000,000
Duration: 9/2017 – 08/2022

Pending
Project title: Cooperative Institute for Earth System Research and Data Science
Supporting agency with grant number: NOAA, Proposal to NOAA-OAR-CIPO-2022-2007108
Investigator months per year: 10.8 months/year
Dollar value: $565,800,000
Duration: 9/2022 - 8/2027

Waleed Abdalati
Director, Cooperative Institute for Research in Environmental Sciences
Professor of Geography, University of Colorado Boulder
waleed.abdalati@colorado.edu

Education

University of Colorado Boulder	Ph.D., Geography/Atmos. and Ocean Sciences, 1996
University of Colorado Boulder	M.S., Aerospace Engineering Sciences, 1991
Syracuse University	B.S., Mechanical and Aerospace Engineering, 1986

Experience

2020- 2021: *Biden-Harris Administration Transition Team*
Reviewed NASA's status, capabilities, and priorities, and developed policy and management recommendations and environmental initiatives for the new Administration.

7/13-pres.: *University of Colorado at Boulder*
Director, Cooperative Institute for Research in Environmental Sciences and Professor, Department of Geography: Lead an 800-person, $100M/year environmental research cooperative institute with NOAA. Conduct research on changes of the glaciers, ice caps, and ice sheets of the world, the mechanisms that drive these changes, and the resulting contributions to sea level.

7/08-6/13: *University of Colorado at Boulder*
Director, Earth Science and Observation Center and Associate Professor, Department of Geography: Led a research organization that works with satellite data to study all aspects of the Earth system and taught classes and developed a curriculum in remote sensing and Earth System Science.

1/11-12/12: *NASA (IPA on leave from CU Boulder)*
Chief Scientist: Advised the NASA Administrator on science matters and as the key NASA scientific interface among NASA, White House, Congress, other federal agencies, international space and science organizations, and industry. Met with Congressional members and staff, provided testimony, evaluated NASA science programs and worked to maximize NASA's scientific capabilities and align them with White House and scientific community priorities. Served on the NASA Executive Council to advise on agency-level strategic decisions.

1/04-6/08: *NASA Goddard Space Flight Center*
Head, Cryospheric Sciences Branch: Supervised a research group of ~12 civil servants and ~40 contractors and postdoctoral scientists, engaged in observation and analysis of sea ice, glacier, and ice sheet processes, primarily through the use of remote-sensing data.

11/00-1/06: *NASA Headquarters, Office of Earth Science / Science Mission Directorate*
Manager, Cryospheric Sciences Program: Managed NASA's interests in cryospheric research, including research funding, particularly in the polar regions. Program Scientist for NASA's Ice Cloud and Land Elevation Satellite (ICESat) mission and RADARSAT mission with the Canadian Space Agency.

4/98-11/00: *NASA Goddard Space Flight Center, Laboratory for Hydrospheric Processes*

Deputy Project Scientist for Ice Cloud and Land Elevation Satellite (ICESat). Contributed to the scientific development of ICESat algorithms and mission activities. Research Scientist: Conducted scientific analysis of airborne laser altimetry data, satellite imagery, ice-penetrating radar data and in situ data on Arctic glaciers for climatological/glaciological interpretation.

Selected Publications

More than 60 peer-reviewed papers, book chapters, and NASA-related technical reports, with over 5000 citations in the peer-reviewed literature and an h-index of 33 (ISI). Snow, Moussavi, and MacFerrin were Ph.D. students.

Snow, T., F. Straneo, J. Holte, S. Grigsby, **W. Abdalati**, T. Scambos (in press). More than skin deep: Sea surface temperature as a means of inferring Atlantic Water variability on the Southeast Greenland continental shelf near Helheim Glacier, *JGR–Oceans*.

Box, J.E, J. Stroeve, **W. Abdalati** (in press). Classics Revisited—Steffen K, Abdalati W and Stroeve J (1993) Climate sensitivity studies of the Greenland ice sheet using satellite AVHRR, SMMR, SSM/I and in situ data. Meteorology and Atmospheric Physics, 239–25, *Progress in Physical Geography*.

Moon, T., T. Scambos, **W. Abdalati**, A. Ahlstrøm, R. Bindschadler, J. Gambill, P. Heimbach, R. Hock, K. Langley, I. Miller, and M. Truffer (2020). Ending a Sea of Confusion: A scientist's perspective on lessons and opportunities in sea level change communication, *Environment: Science and Policy for Sustainable Development*.

Moussavi, M., A. Pope, A.R.W. Halberstadt, L.D. Trusel, L. Cioffi, **W. Abdalati** (2020). Antarctic Supraglacial lake detection using Landsat 8 and Sentinel-2 imagery: towards continental generation of lake volumes, *Remote Sensing*, 12(1), doi: 10.3390/rs12010134.

MacFerrin, M., and 13 others, including **W. Abdalati** (2019) Rapid expansion of Greenland's low-permeability ice slabs, *Nature*, doi: 10.1038/s41586-019-1550-3.

Abdalati, W., and 18 others, *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space 2017*.: The National Academies Press, National Academy of Sciences, Engineering, and Medicine, doi: https://doi.org/10.17226/24938, 2018, 716 pp.

Funding: PI on more than $6.3M in support from NASA over a 20-year period, and Co-I on an additional $9.7M of grants from NASA, NSF, and DOE. PI of the ~$350M Cooperative Agreement with NOAA (NA17OAR4320101).

Teaching: Introductory and advanced remote sensing classes, freshman Earth System class, and graduate seminar in climatology. Primary advisor for 6 Ph.D. students, one Masters student, and one undergraduate honors student. Have served or am serving on 19 Ph.D. Thesis Committees. Also supervised/mentored 9 postdoctoral scholars.

Keynote lectures and outreach: Featured lectures and keynote addresses to the United Nations (UNESCO), AGU, AIAA, SPIE, etc., as well as public lectures at the Smithsonian Institution, American Museum of Natural History, Adler Planetarium, and more. Briefings to White House officials, members of Congress and their staff on Earth remote sensing issues. National Media: Interviews in a wide range of National media outlets (ABC, NBC, CBS, CNN, NPR, BBC, NY Times, etc. as well as local media). Hosted a four-part science series on PBS, and have been featured in two NOVA television shows, and have appeared in various other documentaries.

Christine Wiedinmyer
Associate Director for Science, Cooperative Institute for Research in Environmental Sciences
Research Professor, Mechanical Engineering
University of Colorado Boulder
chrstine.wiedinmyer@colorado.edu

Education

The University of Texas at Austin	Ph.D., Chemical Engineering, December, 1999
The University of Texas at Austin	M.S. Chemical Engineering, 1998
Tulane University, New Orleans, LA	B.S.E. Chemical Engineering, *Cum Laude*, 1994

Post-Graduate Work Experience

2017-pres.	*Assoc. Director of Science*, CIRES, University of Colorado Boulder
2019-pres.	*Research Professor*, Dept. of Mech. Eng., University of Colorado Boulder
2005-2017	*Scientist I-III*, ACOM, National Center for Atmospheric Research, Boulder, CO
2001-2005	*Project Scientist I*, ACD National Center for Atmospheric Research, Boulder, CO
2001	*Research Associate*, University of Colorado, CIRES/NOAA, Boulder, CO
2000-2001	*Research Faculty*, Dept. of Mech. Eng., University of Denver, Denver, CO

Publications

Total Peer-Reviewed: 134; h index=49/64 (ISI/Google Scholar) as of January 2022
Full publication list: http://cires.colorado.edu/administration/christine-wiedinmyer

Selected Publications from last 3 years (22 total - all available on request)

Kiely, L., Spracklen, D.V., Arnold, S.R., Papargyrpoulou, E., Conibear, L., **Wiedinmyer, C.**, et al. (2021) Assessing costs of Indonesian fires and the benefits of restoring peatland. *Nature Comms* 12, 7044, https://doi.org/10.1038/s41467-021-27353-x.

Angot, H., Davel, C., **Wiedinmyer, C.,** et al. (2021). Temporary pause in the growth of atmospheric ethane and propane in 2015–2018. *Atmos. Chem. Phys*., 21, 15153–15170, 10.5194/acp-21-15153-2021.

Harkins, C., McDonald, B.C., Henze, D.K. & **Wiedinmyer, C.** (2021). A fuel-based method for updating mobile source emissions during the COVID-19 pandemic. *Env. Res. Letts*., 16(6), 10.1088/1748-9326/ac0660.

O'Lenick, C.R., Baniassadi, A., Michael, R., Monaghan, A., Boehnert, J., Yu, X., Hayden, M.H., **Wiedinmyer, C.,** et al. (2020). A Case-Crossover Analysis of Indoor Heat Exposure on Mortality and Hospitalizations among the Elderly in Houston, Texas. *Env. Health Persp*., 128(12), 10.1289/EHP6340.

Kiely, L., Spracklen, D.V., **Wiedinmyer, C.**, Conibear, L., Reddington, C.L., Arnold, S.R., Knote, C., Khan, M.F., Latif, M.T., Syaufina, L., & Adrianto, H.A. (2020). Air quality and health impacts of vegetation and peat fires in Equatorial Asia during 2004-2015. *Env. Res. Letts*., 15(9), 10.1088/1748-9326/ab9a6c.

Carter, T. S., Heald, C. L., Jimenez, J. L., Campuzano-Jost, P., Kondo, Y., Moteki, N., Schwarz, J. P., **Wiedinmyer, C.**, et al. (2020). How emissions uncertainty influences the distribution and radiative impacts of smoke from fires in North America. *Atmos. Chem. Phys*., 20, 2073–2097, 10.5194/acp-20-2073-2020.

Wang, C.-T., **Wiedinmyer, C.**, et al. (2019). Potential regional air quality impacts of cannabis

cultivation facilities in Denver, Colorado. *Atmos. Chem. Phys*., 19, 13973–13987, 10.5194/acp-19-13973-2019.

Li, F., Val Martin, M., Andreae, M. O., Arneth, A., Hantson, S., Kaiser, J. W., Lasslop, G., Yue, C., Bachelet, D., Forrest, M., Kluzek, E., Liu, X., Mangeon, S., Melton, J. R., Ward, D. S., Darmenov, A., Hickler, T., Ichoku, C., Magi, B. I., Sitch, S., van der Werf, G. R., **Wiedinmyer, C.**, & Rabin, S. S. (2019). Historical (1700–2012) global multi-model estimates of the fire emissions from the Fire Modeling Intercomparison Project (FireMIP). *Atmos. Chem. Phys*., 19, 12545–12567, 10.5194/acp-19-12545-2019.

Kiely, L., Spracklen, D.V., **Wiedinmyer, C.**, et al. (2019). New estimate of particulate emissions from Indonesian peat fires in 2015. *Atmos. Chem. & Phys*., 19 (17) 11105-11121, 10.5194/acp-19-11105-2019.

Piedrahita, R., Coffey, E.R., Hagar, Y., Kanyomse, E., **Wiedinmyer, C.**, et al. (2019). Exposures to Carbon Monoxide in a Cookstove Intervention in Northern Ghana. *Atmosphere*, 10(7), 10.3390/atmos10070402.

Pfotenhauer, D.J., Coffey, E.R., Piedrahita, R., Agao, D., Alirigia, R., Muvandimwe, D., Lacey, F., **Wiedinmyer, C.**, et al. (2019). Updated Emission Factors from Diffuse Combustion Sources in Sub-Saharan Africa and Their Effect on Regional Emission Estimates. *Env. Sci. & Tech*., 53 (11) 6392-6401, 10.1021/acs.est.8b06155.

Olenick, C.R., Wilhelmi, O.V., Michael, R., Hayden, M.H., Baniassadi, A., **Wiedinmyer, C.**, et al. (2019). Urban heat and air pollution: A framework for integrating population vulnerability and indoor exposure in health risk analyses. *Sci. of the Tot. Env*., 660 715-723, 10.1016/j.scitotenv.2019.01.002.

Archer-Nicholls, S., Lowe, D., Lacey, F., Kumar, R., Xiao, Q., Liu, Y., Carter, E., Baumgartner, J., & **Wiedinmyer, C.** (2019). Radiative Effects of Residential Sector Emissions in China: Sensitivity to Uncertainty in Black Carbon Emissions. *Geophys. Res.-Atmos*., 124 (9) 5029-5044, 10.1029/2018JD030120.

Selected Professional Service

2019-pres.	Trustee, University Corporation for Atmospheric Research
2004-pres.	Board Member, Treasurer and Co-Founder, Earth Science Women's Network (ESWN), a peer-mentoring organization for the support and retention of women in the Earth Sciences
2019-2020	Committee Member, National Academies of Science: Workshop on wildfires, air quality and health
2015-2016	Committee Member¸ National Academies of Science: The Future of Atmospheric Chemistry Research

Selected Honors

2014 Thomson Reuters Highly Cited Researcher
2014 American Meteorological Society: Walter Orr Roberts Lecturer
2011-pres. Lecturer, Assoc. for Women Geoscientists Distinguished Lecture Series
2011 UCAR Diversity Award
2001 Atmospheric Chemistry Colloquium for Emerging Senior Scientists (ACCESS VI) invitee

Appendix 4: CIRES Diversity, Equity, and Inclusion (DEI) Strategic Plan

Introduction

CIRES is committed to fostering diversity within our workplace and to establishing an inclusive culture where people of all identities can thrive. To realize this commitment is not only right, but it also supports research and education excellence. CIRES is working to make justice, equity, diversity, and inclusion core elements of our systems and practices across the institute.

This plan is meant to clarify the CIRES DEI vision, with our shorter-term mission, strategic imperatives, and initial tactics defined. The plan outlines who is responsible for the strategies associated with each imperative, and how success is indicated.

This CIRES DEI strategic plan has been led by the Director of the CIRES Diversity and Inclusion program, with the help of an expert strategic planner, a strategic planning committee drawn from across CIRES, CIRES-wide feedback, and comment from CIRES leadership and external reviewers. Success will depend upon ownership and action throughout the institute.

We will elaborate on this plan with data and timelines as we proceed. It is a living document and we will publish updates on our progress as we go. We are always happy to hear feedback from CIRES employees, partners, and prospective students or employees at any time.

Director's Statement

Dear CIRES colleagues,

CIRES is working to enact diversity, equity, and inclusion and justice among our core values. We choose to do this because it is the right thing to do and is a matter of integrity and because doing so is a cornerstone of our continued success.

We are committed to doing the work it will take to enact these values, which will require commitment and effort across the institute and at all levels. We pledge to ensure that CIRES is a place where the talents of all individuals are cultivated, recognized, and appreciated, which requires a hard look at our processes and outcomes.

As Director of CIRES, I am personally committed to this effort because to me, diversity, equity, inclusion, and justice, are far more than words that capture important concepts; they are values - values we should not just try to live up to, but commit to achieving and surpassing.

This CIRES DEI plan includes strategic intentions meant to ensure that our culture is one that supports and enhances our ability to recruit and retain a diverse workforce, and our ability to establish meaningful powerful partnerships. We commit to transparency throughout the process, and we always welcome your feedback on our plans and your thoughts on how we can do better.

Please join us in promoting DEI efforts at CIRES, in whatever capacity is appropriate for your role. We all have a greater sphere of influence than we know.

Thank you for your active support of these efforts, and your commitment to the principles that drive them.

Waleed Abdalati

Our Process

This plan was developed by a strategic planning committee, led by Susan Sullivan, CIRES Director of Diversity and Inclusion, and Michael Murray, CU Boulder Assistant Vice Chancellor for Strategic Initiatives. The plan was reviewed by expert reviewers external to CIRES.

Members of the CIRES DEI Strategic Planning Committee:

Hazel Bain
CIRES Research Scientist
Space Weather Prediction Center

Joost de Gouw
Professor of Chemistry
CIRES Council of Fellows

Janet Garcia
Visa Coordinator
CIRES Human Resources

Leslie Hartten
CIRES Research Scientist
NOAA Physical Sciences Laboratory

Michael Murray
Assistant VC of Strategic Initiatives
CU Boulder Human Resources

Gabrielle Petron
CIRES Research Scientist
NOAA Global Monitoring Laboratory

Neesha Schnepf
CIRES Postdoctoral Associate
NOAA National Centers for Environmental Information (now at Maxar Technologies)

Susan Sullivan
CIRES Director of Diversity and Inclusion

Chris Torrence
Software Development Manager
CIRES/National Snow and Ice Data Center

Christine Wiedinmyer
CIRES Associate Director for Science

Christina Williamson
CIRES Research Scientist
NOAA Chemical Sciences Laboratory

CIRES DEI Vision and Mission

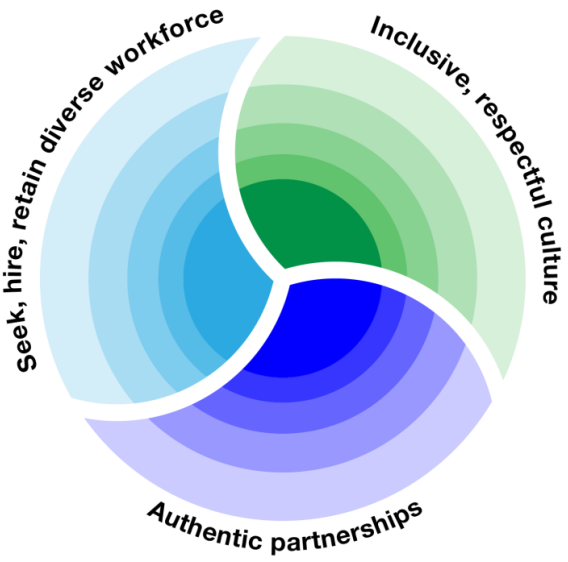
Our science, our communities, and our people thrive when we include, value, and advance a diverse workforce. Nonetheless, our disciplines have not sufficiently attracted, retained, and advanced under-represented and marginalized people. To strive for greater justice, equity, diversity, and inclusion, CIRES commits to the vision and mission below.

Our vision is what we will work to achieve within five years. Our mission introduces the strategic imperatives we will pursue over the next 1-2 years. The plan, the imperatives, and the strategies we use to achieve our vision will be assessed continuously.

Vision:
Justice, equity, diversity, and inclusion are core values at CIRES. Our lived commitment to these values shapes our work culture and is essential to how we practice excellence and integrity in environmental research.

Mission:
CIRES will advance justice, equity, diversity, and inclusion in these ways:

- Continue to build an inclusive, respectful culture that recognizes and embraces the diversity of our communities.
- Increase CIRES' ability to successfully seek, hire, and retain a diverse workforce.
- Increase partnerships with organizations that serve underrepresented and marginalized groups in environmental sciences.



Glossary
Core values: The principles that guide an organization's behavior. Core values form the foundation on which we perform work and conduct ourselves. To be core, a value must be embodied throughout an organization's systems, practices and policies.
Justice: The consistent and systematic fair and impartial treatment of all individuals, including individuals who belong to groups that have been denied such treatment.
Equity: The practice of taking action as needed so that equality can be achieved. Examples include providing employee resource groups or identifying and rectifying systemic compensation issues.
Diversity: the range of human differences. At CIRES these include but are not limited to the CU Protected Classes: race, color, national origin, sex, pregnancy, age, disability, creed, religion, sexual orientation, gender identity, gender expression, veteran status, political affiliation, and political philosophy. We recognize that individuals embody multiple dynamic intersecting and intersectional identities.
Inclusion: Organizational practices in which different groups or individuals are accepted and welcomed and treated equally. In an inclusive culture, all people feel a sense of belonging and are valued and respected for who they are.
Communities: We use the plural "communities" to recognize that there are multiple overlapping groups of people who work at CIRES and to describe the people we work with through education, service, and research.

Culture: The set of shared attitudes, values, goals, and practices that characterizes an institution or organization
Underrepresented groups: An underrepresented group is any group holding identities that are present in lower proportions than occurs in the general population.
Marginalized groups: Any group holding identities that have been systematically excluded from full participation in environmental sciences and scientific research and education.
Partnerships: An arrangement by which two or more parties agree to develop, manage and operate an enterprise and to share equitably in the costs and benefits of the enterprise.
Environmental sciences: We are using environmental science as a shorthand to signify all activity at CIRES, including environmental sciences, geosciences and geophysics, space sciences, social sciences, environmental education, policy, communications, administrative support, and all other related disciplines represented at CIRES.
Environmental research: This is also broadly defined for these purposes and includes research, education and education research, assessments, monitoring, operations, and all other related activities at CIRES.
Indicators: The qualitative and quantitative means by which we assess whether or not we are achieving our goals as anticipated.

Why invest in DEI at CIRES?

There are at least two lines of reasoning which support CIRES' investment in DEI, drawn from a commitment to integrity and to scientific excellence.

Scientific Integrity
Attention to DEI is part of scientific integrity and geoethics, concerned with the responsible conduct of science.[362–364] Investing in a more inclusive workplace culture serves scientific integrity in its highest sense.

- In an inclusive culture, all individuals belong, are respected for who they are, and are valued, including individuals from groups that have not historically been afforded that treatment. Marginalized people working in historically majority-dominated workplaces experience disproportionate barriers and burdens to their well-being unless that workplace is made intentionally and systematically inclusive, just, and equitable.
- Our work has implications for the coupled human and natural systems, in which some communities are disproportionately affected by environmental issues and are often overlooked within environmental sciences research.
- We participate in the University of Colorado educational mission through our outreach, teaching, service, and training activities. The CU student body, including graduate students and other trainees, is increasingly diverse. Our students and trainees have better outcomes when CIRES supports inclusive education and mentoring.

Given these realities, it is only right to develop a workplace in which DEI is realized through our operations and our mission. While there is a strong scientific business case for DEI, the case for scientific integrity precedes.

Scientific Excellence
CIRES would pursue DEI regardless of the scientific business case. In addition, we understand that successful DEI progress supports our scientific achievements.

- Diverse perspectives lead to better problem solving and innovation.[365–369] Diverse author teams have more scientific citations and publish in higher impact journals.[370]
- The student body in environmental sciences and geosciences in the United States is increasingly diverse.[371] Universities and institutes that want to attract and retain an increasingly diverse student body pay attention to representation and an inclusive culture.
- Our ability to secure sponsored funding is increasingly dependent on our ability to demonstrate an inclusive culture, conduct projects with diverse teams and inclusive management, and engage diverse stakeholders in our work. Our primary partners[26,372] and funders[26,373,374] all have diversity and inclusion as part of their expectations.
- Equitable partnerships with communities allow CIRES to conduct more innovative and impactful research. Through partnerships and community co-development, we can ask different questions, access research sites, and develop more relevant and useful research agendas.

None of this is simple. These cases intersect and build on one another, they are not one-dimensional. Success will depend on our ability to thoroughly examine and invest in JEDI as we progress through layers of organizational and personal/individual growth, with a spirit of learning and curiosity.

CIRES DEI Maturity Model

As organizations develop along their DEI journey, their activities become more integrated, sustainable, systematic, and well-understood. Organizations can assess their progress using a DEI maturity model.

Our initial maturity model is primarily based on the Korn Ferry DEI Maturity Model,[375] with contributions from the Meyer DEI Spectrum Tool[376] and the NOAA DEI Maturity Model.[377] All of these models describe DEI maturity as an organizational development activity, which becomes operationalized as essential to the mission. As organizations progress, responsibility is held throughout the organization, resources are available throughout the organization, and actions are prioritized and decided upon based on evidence. CIRES may choose to adapt our model in the future as our understanding of justice, equity, diversity, and inclusion within a research institute improves.

While the full model is laid out in a linear fashion, progress may be non-linear and the paths of each subunit will have variations unique to that group. Progress towards a consistent and mature state requires systematic action across the Institute. View the full maturity model at the link below.

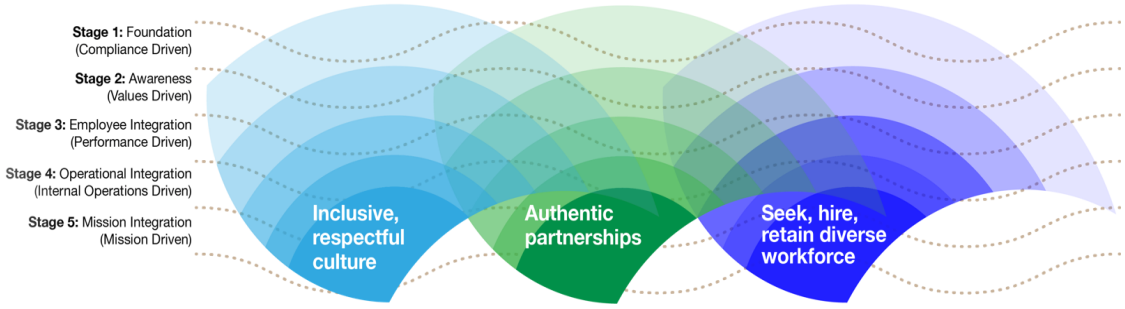


Figure 2: Success depends upon developing a mature organizational approach to DEI, in which commitments and resources are strengthened across the institute in all strategic intent areas. Link to the full maturity model description.

Strategic Imperatives Summary

This first CIRES DEI strategic plan is built around three imperatives. These imperatives were the top three goals identified by the strategic planning committee during their 2020/2021 meetings. Each strategic intent is elaborated in the following sections, along with a description of indicators of success.

Strategic Imperative #1: Build an inclusive, respectful culture that recognizes and embraces the diversity of our communities.
Improve and value supervision and mentorship
Enable and encourage DEI work/training
Improve the safety and inclusion of spaces and language
Strategic Imperative #2: Increase CIRES' ability to successfully seek, hire, and retain a diverse workforce.
Increase and scale use of best practices hiring strategies
Continue and enhance recruiting efforts
Partner with and support campus affinity groups and employee resource groups
Leverage CIRES and CU programs and mechanisms to increase the diversity of hires
Monitor the outcomes of our recruiting, hiring, and retention efforts
Strategic Imperative #3: Increase partnerships with organizations that serve underrepresented and marginalized groups in environmental sciences.
Develop meaningful strategic partnerships with minority-serving institutions (MSI) as part of our NOAA recompete proposal
Promote collaborations through exchange of seminar speakers with minority-serving institutions and other relevant organizations and events

Table 1: Summary of strategic imperatives

Strategic Imperative Objectives and Strategies

Each strategic imperative is further elaborated below, along with a description of the metrics we will use to assess our progress and the people and groups involved.

Strategic Imperative #1: Build an inclusive, respectful culture that recognizes and embraces the diversity of our communities.		
Improve and value supervision and mentorship		
TACTICS	INDICATORS	PARTICIPATING/RESPONSIBLE
Define and develop competencies for inclusive supervision	Documents exist, professional development exists, % supervisors trained on competencies	CIRES HR, CU HR, D&I
Establish assessment mechanisms for inclusive supervision	Policies exist, new assessment mechanisms enacted, follow-through is documented	CIRES HR, CIRES Leadership, D&I
Build capacity for inclusive mentoring	New practices enacted in policy, PD exists, evaluation results, culture survey results	CIRES Mentoring Program, Fellows, CIRES HR, D&I
Establish mechanisms to value inclusive supervision and mentoring	New policies and resources are in place	CIRES HR, SMT
Enable and encourage DEI work/training		
Recognize DEI effort as part of performance management, promotion and recognition requirements.	DEI criteria enacted in policy and communications, application and committee expectations, % inclusion in ASA	CIRES HR, CMC, Fellows
Continue and expand DEI training at CIRES	% who attend, scope and sequence publicized, assessments, culture survey. Presence in workplan(s), prompt exists in ASA workplan	D&I, CIRES HR, Unit Leadership, PIs
Include CIRES-specific DEI content in onboarding	% new hires who participate, % existing employees who use content	D&I, CIRES HR, Unit Leadership
Consistent, widespread communication of CIRES DEI efforts	Web statistics, track activity	D&I, Comms, IT, Unit Leadership
Ensure spaces and language are safe and inclusive		
Review and improve website accessibility and inclusive language	Report on findings, new practices/policies	IT, D&I, Comms
Assess and continue to build a culture of civility and respect	Culture survey, pulse surveys	CIRES HR, D&I, Unit Leadership

Assess and improve accessible and safe physical spaces	Assessment findings, disaggregated culture survey	Facilities, SMT, D&I, Unit Leadership, Campus Leadership

Table 2: Strategic Imperative 1: Objectives, tactics, indicators and participating/responsible parties

Strategic Imperative #2: Increase CIRES' ability to successfully seek, hire, and retain a diverse workforce.		
Increase and scale use of best practices hiring strategies		
TACTICS	INDICATORS	PARTICIPATING/RESPONSIBLE
Systematize and require use of CIRES Best Practices Hiring Guide	% adherence, work products	CIRES HR, Hiring Managers, D&I
Assess and communicate applicant and hiring metrics	Open vs targeted search, applicant/hired demographics	CU HR, CIRES HR, D&I, Hiring Managers
Continue and enhance recruiting efforts		
Continue to exhibit at minority serving science conferences (NABG, SACNAS, AISES)	# engaged, # CIRES employees participating, anecdotal outcomes where systematic assessment does not exist	D&I
Continue to maintain external communications and relationship building	Website redesign and update, information interviews, external mailing list # and engagement	D&I, Comms, IT
Promote campus affinity groups and employee resource groups		
Promote and support inter-institute affinity group(s)	Demonstrable actions	D&I, Inter-Institute Committee
Regularly communicate about and support participation in campus affinity groups and ESG	Culture survey, demonstrable actions	D&I, Comms, Supervisors
Leverage CIRES and CU programs and mechanisms to increase the diversity of hires		
Leverage existing CU mechanisms to increase diversity (e.g. Advance Preview, VFP, FDAP, Chancellor's Postdoctoral Scholars, etc.)	Description of advances, demographics	Fellows, PIs, CIRES HR, SMT
Increase connections between CIRES recruiting efforts and entry into partner programs (e.g. departmental admissions, NOAA internship opportunities)	# applicants/placements	Partners, D&I, PIs

Monitor the outcomes of our recruiting, hiring and retention efforts.		
Monitor and communicate Institute metrics with attention to privacy and safety	Communicated metrics (e.g. civility, demographics, applicant pool demographics, retention), DEI dashboard	SMT, DEI, CIRES HR, CU HR, Comms, IT
Identify and address any systematic equity issues	Findings and actions	CIRES HR, CIRES Leadership, Unit Leadership, D&I

Table 3: Strategic Imperative 2: Objectives, tactics, indicators and participating/responsible parties

Strategic Imperative #3: Increase partnerships with organizations that serve underrepresented and marginalized groups in environmental sciences.		
Develop meaningful strategic partnerships with minority-serving institutions (MSI) as part of our NOAA Cooperative Agreement (CA) proposal		
TACTICS	INDICATORS	PARTICIPATING/RESPONSIBLE
Draft CA proposal with collaboration of Cooperative Science Centers (CSC)	DEI included in CA proposal	D&I, SMT, Partners
Establish co-advising and fellowship/internship opportunities	Programmatic elements exist and are being used	D&I, CIRES Researchers, Partners
Promote collaborations through exchange of seminar speakers with minority serving institutions and other relevant organizations and events		
Provide opportunities for CIRES employees to present at minority-serving conferences	Number of employees who participate	SMT, Supervisors, D&I
Arrange site visits, exchanges and speaking opportunities	# visits, exchanges, talks	D&I, Seminar Leaders, Partners

Table 4: Strategic Imperative 3: Objectives, tactics, indicators, and participating/responsible parties

Roles and Responsibilities

To succeed in achieving our mission and vision over the next two to five years will require a concerted effort, which will take participation and leadership within every level of CIRES. Every person at CIRES has a sphere of control and influence, which is often larger than one imagines. Roles for people at every level are described below.

Roles	**Responsibilities**
Senior Leadership	Ensure that organizational systems, policies and practices support CIRES DEI vision and are

	integrated into CIRES operations.
CIRES D&I Program	Oversee CIRES DEI plan, annual report and performance measurement. Manage DEI projects at CIRES programmatic level. Advise CIRES leadership and support subunits to achieve these Diversity and Inclusion Strategic Plan goals. Establish policies and procedures that directly support plan objectives.
CIRES HR	Provide direction and support in achieving DEI Strategic Plan goals, to include: leading workforce planning and analysis; hiring; talent management (e.g., training and onboarding); processes; and policies.
Hiring Managers and Search Committees	Comply with diversity hiring and selection principles, work with CIRES DEI/HR and CU HR to recruit a broad and diverse talent pool and employ techniques to interrupt bias and promote fairness.
Advisors and Mentors	Serve as a resource for students, peers and employees. Follow inclusive mentoring practices to help mentees thrive.
Supervisors	Follow inclusive performance management and supervision principles. Participate in and apply the principles within CIRES and CU best practices training.
Every CIRES Team member	Individually advance CIRES' diversity and inclusion goals by cultivating a respectful culture, following and promoting diversity, equity and inclusion principles, and recognizing and interrupting implicit biases.

Table 5: Responsibilities within different roles at CIRES.

Achieving Results

CIRES' success will be supported by our ability to implement this DEI strategic plan. The CIRES D&I Director, in partnership with CIRES HR and other CIRES Leadership, will lead the implementation.

CIRES Leadership will engage the CIRES workforce as appropriate to advance these objectives and will provide support and resources to achieve results.

This document is a living plan. The execution of this plan may be influenced in response to our changing understanding and opportunities. We will monitor our progress toward our objectives and regularly share our progress towards the strategic intents in this plan. Successful implementation will lead to a workplace in which our scientific excellence is matched by our excellent inclusive culture.

Appendix 5: Results of the Most Recent CIRES Reviews

2017 University of Colorado Boulder Program Review, Academic Review and Planning Advisory Committee Report

Unit Overview: "The internal reviewers note that 'CIRES is a premier, world-renown research institute and a significant benefit to the teaching and research mission of CU.' The external reviewers agree with this assessment and deem CIRES to be 'an international leader in Earth systems and environmental science research with an ambitiously broad yet high-quality research program.' The institute's success in research productivity and extramural funding is impressive, and its faculty have won prestigious university, national, and international awards." The full report is available upon request.

2016 external NOAA review of CIRES :

The following are select highlights quoted directly from the report, which is available in full upon request or can be found in the NOAA Science Advisory Board web page report library.

Summary

"The review panel found the CIRES research programs, directed by the leadership team of Waleed Abdalati (Director) and Kristen Averyt (Associate Director for Science), to be essential to the successful research operations of NOAA and is also critical to the University of Colorado. The review panel unanimously agreed to a performance rating for CIRES of OUTSTANDING. No significant areas of concern were identified, and the recommendations put forth in this review by the committee are provided as merely suggestions to help CIRES continually improve…"

Overall findings by the review committee:

- "The relationship between NOAA, CIRES, and the University of Colorado is of great benefit to all three entities. CIRES is essential to the successful research operations of NOAA and is critical to those at the University of Colorado.
- CIRES is highly regarded within the University and is broadly engaged.
- The CIRES Director, Waleed Abdalati, is highly regarded by NOAA, CIRES, CU, and the broader science community. He received particularly high praise from the NOAA division directors during the CIRES Review."

"The review panel unanimously agreed to a performance rating for CIRES of OUTSTANDING. The recommendations put forth in this review by the committee are provided as merely suggestions to help CIRES continually improve."

Appendix 6: Acronyms and Abbreviations

ACCLIP: Asian Summer Monsoon Chemical and Climate Impact Project
ACE: Architecture for Collaborative Evaluation
ADAPT: Air Force Data Assimilative Photospheric Flux Transport
ADS: Associate Director for Science
AEROMMA: Atmospheric Emissions and Reactions Observed from Megacities to Marine Areas
AGI: American Geosciences Institute
AGU: American Geophysical Union
AI: Artificial Intelligence
AMS: American Meteorological Society
AMSR: Advanced Microwave Scanning Radiometer
AOD: Aerosol Optical Depth
AQPI: Advanced Quantitative Precipitation Information
ARL: NOAA Air Resources Laboratory
ARM: Advanced RISC Machines
ATom: ATmospheric Tomography
ATOMIC: Atlantic Tradewind Ocean-Atmosphere Mesoscale Interaction Campaign
ATOMS: AWIPS Tsunami Operations Messaging Service
AWAKEN: American WAKE Experiment
AWIPS: Advanced Weather Interactive Processing System
AWRP: Aviation Weather Research Program
AWS: Amazon Web Services
CAFS: Coupled Arctic Forecast System
CAM: Community Atmosphere Model
CARE: Colorado AI Research for the Environment
    also: Collective Benefit, Authority of Control, Responsibility and Ethics
CARI: Civil Aviation Research Institute
CAT: coronal mass ejection analysis tool
CCOR: Compact Coronagraph
CCPP: Common Community Physics Package
CDA: Coupled Data Assimilation
CFC-11: Chlorofluorocarbon-11
CFCs: Chlorofluorocarbons
CFS: Coupled Forecast System Model
CGA: CIRES Graduate Association
CI: Cooperative Institute
CICE: The Los Alamos Sea Ice Model
CIESRDS: Cooperative Institute for Earth System Research and Data Science
CIRA: Cooperative Institute for Research on the Atmosphere
CIRES: Cooperative Institute for Research in Environmental Sciences
CLEAN; Climate Literacy and Energy Awareness Network
CMAQ: Community Multiscale Air Quality
CMC: CIRES Members Council
CMIP: Coupled Model Intercomparison Project
Comms: CIRES Communications Group
CO-LABS: Colorado Leveraging Assets for Better Science
CONUS: Contiguous United States
COSMIC-2: Constellation Observing System for Meteorology, Ionosphere and Climate-2
CPC: NOAA Climate Prediction Center
CPU: Central Processing Unit
CSB: Crowdsourced Bathymetry
CSC: Cooperative Science Center
C-SEF: Center for Social and Environmental Futures
CSL: NOAA Chemical Sciences Laboratory
CSV: Comma Separated Values
CTIPe: Coupled Thermosphere Ionosphere Plasmasphere Electrodynamics Model
CU: University of Colorado
CUPiDS: Coastal Urban Plume Dynamics Study
DA: Data Assimilation
DAAC: Distributed Active Archive Center
DOE: Department of Energy
DEI: Diversity, Equity and Inclusion
DEM: Digital Elevation Model
DEWS: Drought Early Warning System

D&I: Diversity and Inclusion, also CIRES Diversity and Inclusion Program
DIAL: differential absorption lidar
DOT: United States Department of Transportation
DSCOVR: Deep Space Climate Observatory
DSRC: David Skaggs Research Center
DWR: California Dept. of Water Resources
ECR: Early Career Researcher
EDDI: Evaporative Demand Drought Index
EEO: Equal Employment Opportunity
EMAG: Earth Magnetic Anomaly Grid
EMC: Environmental Modeling Center
ENRR: El Niño Rapid Response
ENSO: El Niño-Southern Oscillation
EPIC: Earth Prediction Innovation Center
EPP/MSI: Educational Partnership Program/Minority Serving Institution
ERASMUS: Evaluation of Routine Atmospheric Sounding Measurements Using Unmanned Systems
ERB: Earth Radiation Budget program
ESWN: Earth Science Women's Network
EUREC^{4}A: Elucidating the role of Clouds-Circulation Coupling in Climate
FACETs: Forecasting a Continuum of Environmental Threats
Facilities: CIRES Facilities Lead
FAIR: Findable, Accessible, Interoperable, and Reusable
Fellows: The CIRES Council of Fellows
FIREX-AQ: Fire Influence on Regional to Global Environments and Air Quality
FIRO: forecast-informed reservoir operation
FITS: Flexible Image Transport System
FPH: Frost-Point Hygrometers
FRP: Fire Radiative Power
FV3: Finite-Volume Cubed-Sphere
GC: gas chromatograph
GEFS: Global Ensemble Forecast System
GEFS-Aerosols: Global Ensemble Forecast System-Aerosols
GeoFLOW: GeoFLuid Object WorkBench
GFDL: Geophysical Fluid Dynamics Laboratory
GFS: Global Forecast System
GHG: Greenhouse Gas
GICs: Geomagnetically Induced Currents
GIS: Geographic Information Systems
Glo-TEC: Global Assimilative Total Electron Content Model
GML: NOAA Global Monitoring Laboratory
GNSS: Global Navigation Satellite System
GOES: Geostationary Operational Environmental Satellite
GOLD: Global-scale Observations of the Limb and Disk
GONG: Global Oscillation Network Group
GPU: Graphics Processing Unit
GSA: Geological Society of America
GSL: NOAA Global Systems Laboratory
HCFCs: hydrochlorofluorocarbons
HDGM: High Definition Geomagnetic Model
HFCs: Hydrofluorocarbons
HORUS: High-Altitude Operational Return Uncrewed System
HPC: High Performance Computing
HR: Human resources
HRRR: High-Resolution Rapid Refresh
HRRR-Smoke: High-Resolution Rapid Refresh-Smoke
ICAO: International Civil Aviation Organization
IDL: Interface Definition Language
INSTAAR: Institute for Arctic and Alpine Research
IDSS: Impact-Based Decision Support Services
IMPD: International Multiproxy Paleofire Database
Inter-Institute Committee: The CU Boulder Institutes JEDI Committee
IPCC: Intergovernmental Panel on Climate Change
IPE: Ionosphere Plasmasphere Electrodynamics
IR: CU Institutional Research
IT: CIRES Information Technology Group
ITRDB: International Tree-Ring Data Bank

JCSDA: Joint Center for Satellite Data Assimilation
JEDI: Justice, Equity, Diversity, and Inclusion
also: Joint Effort for Data Assimilation Integration
JSON: JavaScript Object Notation
LAPSE-RATE: Lower Atmospheric Profiling Studies at Elevation
LASP: Laboratory for Atmospheric and Space Physics
LASIC:
LES: Large Eddy Simulations
LIM: Linear Inverse Model
MADIS: Meteorological Assimilation Data Ingest System
MASIE-AMSR2: Multisensor Analyzed Sea Ice Extent - Advanced Microwave Scanning Radiometer 2
MET: Model Evaluation Tools
MJO: Madden-Julian Oscillation
ML: machine learning
MOM: Modular Ocean Model
MOSAiC: Multidisciplinary Drifting Observatory for the Study of Arctic Climate
MSI: Minority Serving Institution
NAS: National Academies Study
NASA: National Aeronautics and Space Administration
NCAP: NESDIS Cloud Archive Project
NCAR: National Center for Atmospheric Research
NCCASC: North Central Climate Adaptation Science Center
NCCF: NESDIS Common Cloud Framework
NCEI: National Centers for Environmental Information
NCEP: National Centers for Environmental Prediction
NCO: NCEP Central Operations
NEON: National Ecological Observatory Network
NERTO: NOAA's Experiential Research and Training Opportunities
NESDIS: National Environmental Satellite Data and Information Service
NFAN: NOAA Federated Aerosol Network
NGA: National Geospatial-Intelligence Agency
NightFox: Nighttime Fire Observations eXperiment
NIDIS: National Integrated Drought Information System
NOAA: National Oceanic and Atmospheric Administration
NOFO: Notice of Funding Opportunity
NREL: National Renewable Energy Laboratory
NSDL: National Science Digital Library
NSF: National Science Foundation
NSO: National Solar Observatory
NSSL: National Severe Storms Laboratory
NSIDC: National Snow and Ice Data Center
NSTA: National Science Teaching Association
NTHMP:National Tsunami Hazard Mitigation Program
NWC: National Water Center
NWM: National Water Model
NWP: Numerical Weather Prediction
NWS: National Weather Service
O2R: Operations-to-Research
OAR: Office of Oceanic and Atmospheric Research
PECASE: Presidential Early Career
PHI: Probabilistic Hazards Information
PI: Principal Investigator
POPEYE: Profiling at Oliktok Point to Enhance YOPP Experiments
PROSWIFT: Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow
PSL: Physical Sciences Laboratory
QBO: Quasi-Biennial Oscillation
QPE: Qualitative Precipitation Estimate
QPF: Quantitative Precipitation Forecast
R2O: Research to Operations
R2O2R: Research-to-Operations-to-Research
RAP: Rapid Refresh

RECCS: Research Experiences for Community College Students
RELeASE: RELativistic Electron Alert System for Exploration
REU: Research Experiences for Undergraduates
RIO: Research & Innovation Office
RISA: Regional Integrated Sciences and Assessments
RO: Radio Occultation
ROTI: Rate-of-Change of TEC Index
ROV: Remotely Operated Vehicle
RPPR: Research Performance Progress Report
RRFS: Rapid Refresh Forecast System
RTMA: Real Time Mesoscale Analysis System
S2D: Seasonal-to-Decadal
S2S: Subseasonal-to-Seasonal
SABRE: Stratospheric Aerosol processes, Budget, and Radiative Effects
SAIL: Surface Atmosphere Integrated Field Laboratory
SCC: Solar Command Center
SENA: Software Engineering for Novel Architectures
SF6: Sulfur Hexafluoride
SMT: Senior Management Team
SOARS: Significant Opportunities in Atmospheric Research and Science
SODA: Stratified Ocean Dynamics of the Arctic
SOS: Science on a Sphere
SOSx: SOS Explorer®
SPLASH: Study of Precipitation, the Lower Atmosphere and Surface for Hydrometeorology
SRS: Solar Region Summary
SSH: Sea-Surface Height
SST: Sea-Surface Temperature
STEREO: Solar Terrestrial Relations Observatory
SUNVEx: Southwest Urban NOx and VOC Experiment
SURFRAD: Surface Radiation Budget Network
SWFO: Space Weather Follow-On
SWOOSH: Stratospheric Water and OzOne Satellite Homogenized
SWPC: Space Weather Prediction Center
TEMPO: Tropospheric Emissions: Monitoring of Pollution
TIM: Threats-In-Motion
TRACER: TRacking Aerosol Convection Interactions ExpeRiment
TROPOMI: TROPOspheric Monitoring Instrument
UCAR: University Corporation for Atmospheric Research
UFS: Unified Forecast System
U.S: United States
USGS: United States Geological Survey
UNEP/WMO: UN Environment Programme/World Meteorological Organization
UTLS: Upper Troposphere/Lower Stratosphere
UxS: Uncrewed Systems
VCPs: Volatile Chemical Products
VFP: Visiting Fellows Program
VIIRS: Visible Infrared Imaging Radiometer Suite
VORTEX-SE: Verification of the Origins of Rotation in Tornadoes EXperiment-Southeast
WAF: Web-Accessible Folder
WAM: Whole Atmosphere Model
WAVE: Weather Archive and Visualization Environment
WDS-Paleo: World Data Service for Paleoclimatology
WFIP3: Third Wind Forecast Improvement Project
WFO: Weather Forecast Office
WiscoDISCO: Wisconsin's Dynamic Influence of Shoreline Circulations on Ozone
WMM: World Magnetic Model
WPC: Weather Prediction Center
WRF: Weather Research and Forecasting Model

WRF-Hydro: Weather Research and Forecasting Model Hydrological Modeling System
WSA: Wang-Sheeley-Arge
WV: Water Vapor
WWA: Western Water Assessment

Appendix 7: National Environmental Policy Act (NEPA) Requirements

Project Title: Cooperative Institute for Earth System Research and Data Science (CIESRDS)

Description of Proposed Activity: The overarching goal of the proposed new cooperative institute, CIESRDS, is to support NOAA with Earth system research and data science on topics of significant societal importance. We propose the thematic projects described in Section 3.B. to:

- Conduct high-quality Earth system research and data science in collaboration with and service to NOAA to support society's resilience to environmental change,
- Train and inspire a diverse and skilled future Earth system and data science workforce for NOAA and beyond,
- Grow Earth system research and data science literacy in learners of all ages,
- Serve the general public and decision-makers with information that fosters resilience to changes in the Earth system, and
- Provide the robust scientific and administrative infrastructure to run a cooperative institute cost-effectively, to successfully fulfill NOAA's needs and objectives. This infrastructure will support growth, given CIRES' trajectory of success in external funding.

Activities: CIESRDS will perform a diverse set of dozens of research projects aligned with several NOAA line offices (OAR, NESDIS, NWS, OE); this work will be conducted cooperatively with NOAA. Activities may include in-field measurements and observations from multiple platforms, instrument development, and deployment, laboratory experiments, modeling activities, development of hardware and software, and much more.

Work Locations: The primary CIESRDS research location is the NOAA David Skaggs Research Center in Boulder, Colorado. Research activities will also take place at the NOAA NWS Weather Prediction Center in College Park, MD. CIESRDS scientists are expected to perform research activities at sites within Colorado, the broader United States, and at international sites critical for specific research activities. Future CIESRDS activities may be located at the University of Colorado Boulder campus. All of these facilities have the infrastructure, IT, and administrative services necessary to support a world-class research enterprise compliant with all appropriate regulations, including NEPA.

Equipment and Duration: CIESRDS will perform short-term (hours, days, weeks) and long-term (months, years) monitoring from Boulder, Colorado, and other key sites throughout the world. The measurement systems will be determined by the needs of the identified future research projects. We expect to have various measurement platforms, including stationary ground sites, mobile labs, research vessels, autonomous platforms, and aircraft (for example, the NOAA P3 and the NASA DC8). Sample and data processing and analysis will be conducted at NOAA facilities or partner institutions. Note: No new building construction is anticipated during the award period.

Review, Mitigation, and Monitoring: All measurements and sample collections protocols will undergo review and will comply with applicable regulations and requirements. CU Boulder employs planners, environmental impacts experts, architects, and other compliance experts, who can support any necessary site review, mitigation, and monitoring, and who serve as liaisons with sponsors and regulatory agencies. As currently scoped, none of our proposed work requires

environmental permitting. If funded, we will work closely with NOAA and CU Boulder to develop our workplan, and in that process, we will identify relevant environmental policies and regulations and ensure compliance.

More broadly, CIESRDS will be an environmental research institute hosted by a campus dedicated to lowering its environmental footprint by minimizing energy use, cutting carbon emissions, and more. Please learn more about CU Boulder's achievements and commitments here: https://www.colorado.edu/sustainability/

Appendix 8: Evaluation Criteria Roadmap

Response to questions posed under selected review criterion in the NOFO section V.A. (Application Review Information, Evaluation Criteria)

1. Importance and/or relevance and applicability of proposed project to the program goals
Does the proposal include research goals and projects that address the critical issues identified in NOAA's 2005 20-year Research Vision, NOAA's Next-Generation Strategic Plan, and the NOAA 20-Year Research and Development Vision Areas: 2020-2026 and the priorities described in the program priorities (see Section I.B.)?

Yes. Our CIESRDS proposal is structured around the research themes outlined in Section I.B. of the Notice of Funding Opportunity (NOFO) and includes a broad range of research goals and projects to address NOAA's 2005 20-year Research Vision, NOAA's Next-Generation Strategic Plan, and the NOAA 20-Year Research and Development Vision Areas: 2020-2026. Section 3.A. of our proposal outlines our overall goals and how the proposed CIESRDS work will help NOAA achieve agency goals outlined in the three critical NOAA strategic documents and two others (NOAA's Education and DEI strategic plans); please see Table 2 for an alignment matrix. Section 3.B. briefly discusses CIRES' past work in each research area and identifies several potential CIESRDS research programs that address NOAA program priorities in each of eight research themes.

Is there a demonstrated commitment (in terms of resources and facilities) to enhance existing NOAA and CI resources to foster a long-term collaborative research environment?

Yes. Established in 1967 and with ~830 people today, the current Cooperative Institute (CIRES) is the largest and one of the oldest of NOAA's CIs, and our mission is tightly aligned with the priorities of the agency. CIRES scientists are integral to the success of the NOAA Boulder laboratories, contributing to nearly every scientific and technical accomplishment. Section 2 highlights key achievements in our long history of service to NOAA, as well as our proven success in leveraging NOAA's cooperative investment with research grants from other agencies and foundations that support research closely tied to NOAA's mission.

CIRES has added value and enhanced the impact of NOAA research and resource management. We employ about 415 people who work embedded in NOAA teams, comprising roughly half of the workforce of NOAA's Earth System Research Laboratories; more than 70 people in the National Centers for Environmental Information, or about two-thirds of NCEI's Boulder workforce; another 28 people in the Space Weather Prediction Center, about 40 percent of the workforce; and 6 in the Weather Prediction Center in Maryland (Section 3.C.2.a.).

Our proposed CI will build on this foundational commitment to foster expanded collaboration between our research university and multiple NOAA line offices. With a robust infrastructure strongly supported by the University of Colorado Boulder and a highly collaborative relationship with our current NOAA partners, we have the resources and facilities to conduct proposed work.

Specific details are provided within each research theme description (Section 3.B.) and in the Institutional Capabilities and Composition Section (3.C.).

2. Technical/scientific merit
Does the project description include a summary of clearly stated goals to be achieved during the five-year period that reflect NOAA's strategic plan and goals?

Yes. In Section 3.A. we outline the overarching goals of the proposed new cooperative institute, CIESRDS, that reflect NOAA's strategic plan and goals. In Section 3.B. we describe in detail the proposed CIESRDS projects and their potential contributions to NOAA's research plan, strategic plan, and goals.

Does the CI involve partnerships with other universities or research institutions, including Minority Serving Institutions, and universities, such as NOAA CSCs, that can contribute to the proposed activities of the CI?

Yes. CU Boulder—CIRES' and CIESRDS' home institution—is a world leader in research, with top international rankings in geosciences and atmospheric sciences. CIRES scientists collaborate regularly with experts across the university, including at INSTAAR and LASP, for example. In addition, CIRES has long-standing relationships with many university, government, and commercial partners that will serve CIESRDS objectives—these range from the individual to the institute level, and many are part of a broad, collaborative research ecosystem in Colorado (Section 3.C.2.b.), including NCAR, NREL, NSO, USGS, NEON, and others. We have led large projects—MOSAiC, for example—that have involved partnerships and collaborations across several research sectors (ecosystems, oceans, atmosphere, cryosphere) and span multiple countries.

CIRES also has had strong success mentoring and supporting students and scholars from underrepresented backgrounds through programs that we either run (e.g., the Research Experiences for Community College Students program and the Tribal Climate Leaders Program) or participate in (Section 3.B.5.). Our proposed CI will continue to build relationships with organizations that support underrepresented and minoritized students and scientists, as well as professional societies that promote DEI in the sciences (Section 3.E.2.). We propose to collaborate and interact with NOAA's Cooperative Science Centers, Experiential Research and Training Opportunities (NERTO), Postdoctoral Fellowships, and the agency's EPP/MSI undergraduate scholarships. We will work to help NOAA meet the workforce and hiring goals set in the agency's Diversity and Inclusion Strategic Plan FY 2020-2024, and propose specific projects aligned with these goals in Section 3.E.2. and Appendix 4.

Does the proposal include a Data Management Plan that is appropriate for work and that addresses the intent of NOAA's Data and Publication Sharing Directive for NOAA Grants, Cooperative Agreements, and Contracts?

Yes. In Section 4, we outline our Data Management Plan, including information on data sharing and how we will address the intent of NOAA's Data and Publication Sharing Directive; how we

will meet the objectives of the NOAA Cloud Strategic plan, through our work in NCEI and SWPC in particular; and details on CIRES' proven data management expertise.

3. Overall qualifications of applicants
If the institution(s) and/or Principal Investigators have received current or recent NOAA funding, is there a demonstrated record of outstanding performance working with NOAA and/or NOAA scientists on research projects?

Yes. CIRES has a demonstrated record of outstanding performance working with NOAA and has made important contributions to the scientific and technical achievements of the NOAA Boulder laboratories. Section 2 highlights some of our key achievements, and specific details are provided within each research theme description (Section 3.B.), including how the proposed CI would build upon our previous work.

As detailed in the Institutional Capabilities and Composition Section (3.C.), our proposed new cooperative institute, CIESRDS, would benefit from years of NOAA engagement and collaboration by CIRES leadership, particularly by the two PIs, Waleed Abdalati and Christine Wiedinmyer (Section 3.C.1.a.). Dr. Abdalati, an expert in climate-related cryospheric changes in Greenland, has extensive experience in high levels of government, academia, and industry. He served as NASA chief scientist and co-chaired a National Academies Study that provided guidance to NOAA and other agencies on the next decade of investments in Earth Observation from Space. Dr. Wiedinmyer is an atmospheric scientist and chemical engineer, and her work has long aligned with NOAA's science. She has published collaboratively with NOAA Boulder colleagues in pollutant emissions, air quality, and the radiative impacts of smoke from wildfires.

In addition, CIRES has earned international and national recognition, including from NOAA, for our science and scientists who support the agency. For example, CIRES scientists are key members and leaders of NOAA teams that earn Department of Commerce Gold, Silver, and Bronze Medals (Section 3.C.), and CIRES-led or CIRES-involved research is featured regularly in NOAA annual Science Reports and in NOAA, NOAA Research, and NCEI news stories and press releases that focus on results of research and the associated social and economic impacts to communities, decision-makers, and the general public.

Is there nationally and/or internationally recognized expertise within the appropriate disciplines needed to conduct the collaborative/interdisciplinary research described in the proposal?

Yes. CIRES has nationally and internationally recognized expertise in research areas closely aligned with the proposed research themes for CIESRDS. The University of Colorado Boulder, CIRES' home institution, has earned top international rankings in geosciences and atmospheric sciences, developed in large part from our years of collaborative work with NOAA (Section 3.C.2.b.). CIRES has earned national recognition, including from NOAA, for our science and scientists who support the agency, as highlighted in Section 2 and in Section 3.C. For example, six CIRES scientists, five of whom worked with NOAA groups, earned Presidential Early Career or PECASE awards during our last cooperative agreement; 11 CIRES scientists are Fellows of the American Geophysical Union or the American Meteorological Society, leading organizations

that conduct NOAA-relevant science; and CIRES scientists contributed to NOAA teams recognized with Department of Commerce Gold, Silver, and Bronze Medals.

CIRES has collaborated with NOAA for 54 years, and our people are both integrated within the agency and essential to the success of the renowned Boulder-based Laboratories and Centers. With scientists, engineers, data analysis experts, developers, students, and other staff embedded in every NOAA Boulder laboratory and within 10 departments across the CU Boulder campus, our proposed CI is well connected and positioned to support NOAA needs and advance NOAA's mission. For example, we highlight our expertise in AL/ML research in Section 3.C.1. and our leadership in the field of UxS applications in Earth system science (Section 3.C.2.b.). We provide additional details on our expertise throughout each Research Theme description (Section 3.B.).

Is there a well-developed business plan that includes fiscal and human resource management, as well as strategic planning and accountability?

Yes. Section 3.E. details the proposed structure, governance and leadership (3.E.1.), administrative, fiscal, and human resource management (3.E.2), strategic planning and accountability (3.E.3.), and administrative support structure for personnel working in NOAA facilities (3.E.2.). Our business plan builds on a very successful history supporting NOAA.

Are there any unique capabilities in a mission-critical area of research for NOAA?

Yes. Our proposed CI encompasses multiple unique capabilities in mission-critical NOAA research areas, as detailed in Section 3.A. Other examples include our expertise in artificial intelligence (3.C.1.b.), UxS (3.C.2.b.), and communications, education, and DEI (3.C.1.c.); two CIRES centers that focus directly on usable science serving society's needs—the Western Water Assessment and the North Central Climate Adaptation Science Center (3.C.2.a.); our new interdisciplinary Center for Social and Environmental Futures (3.C.2.b.); and collaborations with CU Boulder's Institute for Arctic and Alpine Research and other federally funded research laboratories (3.C.2.b.).

Throughout Section 3.B., we provide specifics on the capability of the proposed CI to address mission-critical areas of research for NOAA. These research programs are designed to extend and expand upon existing CIRES work, ensuring that we continue to produce world-class Earth system research and data science—in service to society and in close collaboration with NOAA.

Has the applicant shown a substantial investment to foster a long-term collaboration with NOAA?

Yes. The Budget Narrative describes cost-share commitments from CIRES and CU Boulder. Section 2 details CIRES' proven track record in leveraging NOAA's cooperative investment by winning research grants from other agencies and foundations to support research closely tied to NOAA's mission.

4. Project costs
The budget is evaluated to determine if it is realistic and commensurate with the project needs and time-frame

The proposed budget was formulated based on CIRES' previous research and operational experience and the potential expansion of CIESRDS activities with these NOAA laboratories/centers: CSL, GML, GSL, PSL, NCEI, SWPC, and the WPC. Details on budget calculations are provided in the Budget Narrative.

5. Outreach and education
Is there a strong education program with established graduate degree programs in NOAA-related sciences that also encourages student participation in NOAA-related research studies?

Yes. CIRES is a world leader in scientific education, training, outreach, and student research engagement in NOAA-related sciences, and as CIESRDS, we propose to expand these activities. Section 3.D. provides a full description of our educational programs, including established graduate degree programs in NOAA-related sciences (3.D.1.) and opportunities for undergraduate research, fellowships, and other avenues for students to participate in NOAA-related research. In addition, in Section 3.B.5. we describe CIESRDS proposed work as it aligns with the NOFO, including work to improve the research enterprise itself, through postdoctoral and visiting scientist programs, and to support graduate education and other early-career scientists. We also outline our plan for improving diversity, inclusion, and equity in the workforce (Section 3.B.5. and Appendix 3).

Appendix 9: Photographs Appearing in this Proposal

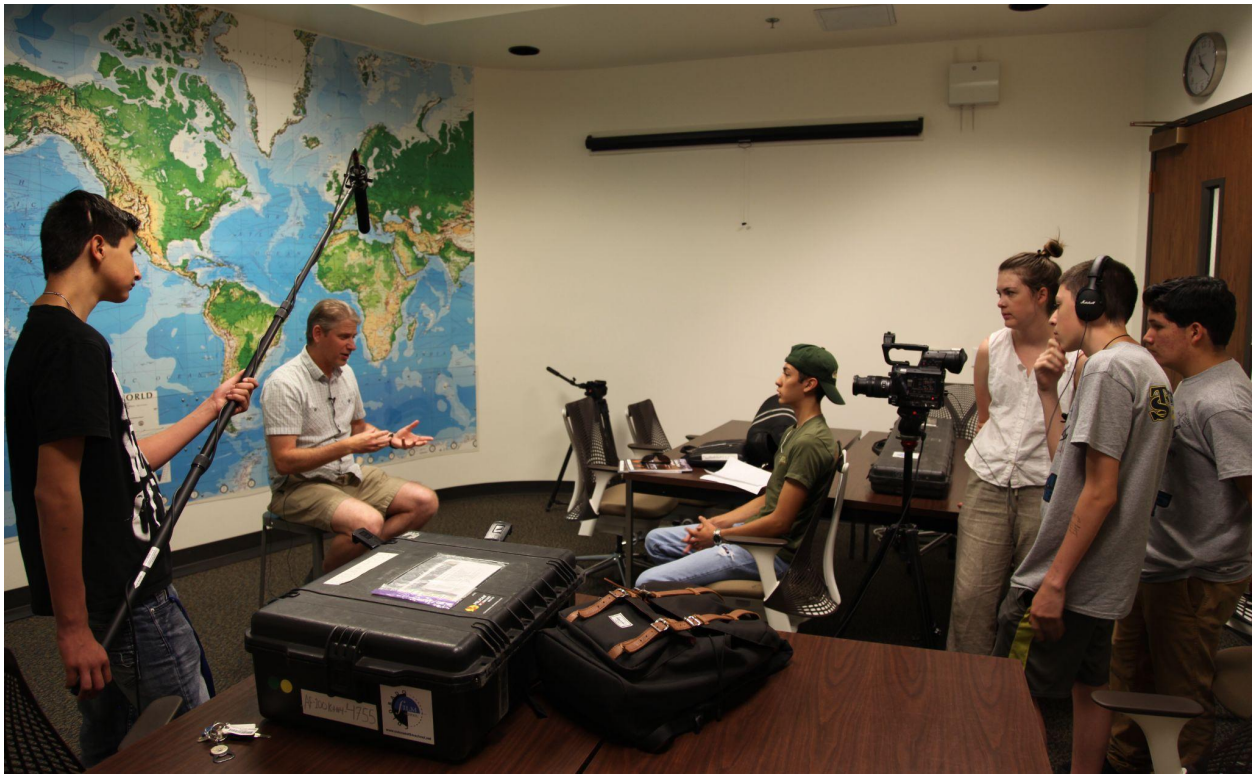
All photos used in this report are by CIRES staff, submitted during biennial photo contests or otherwise shared with the institute in the last 10 years.

Section 3.B.1. Future Atmosphere
Rays of the rising sun light up thick layers of smoke from a forest fire in North Cascades National Park, Washington. Photo: Mylene Jacquemart/CIRES

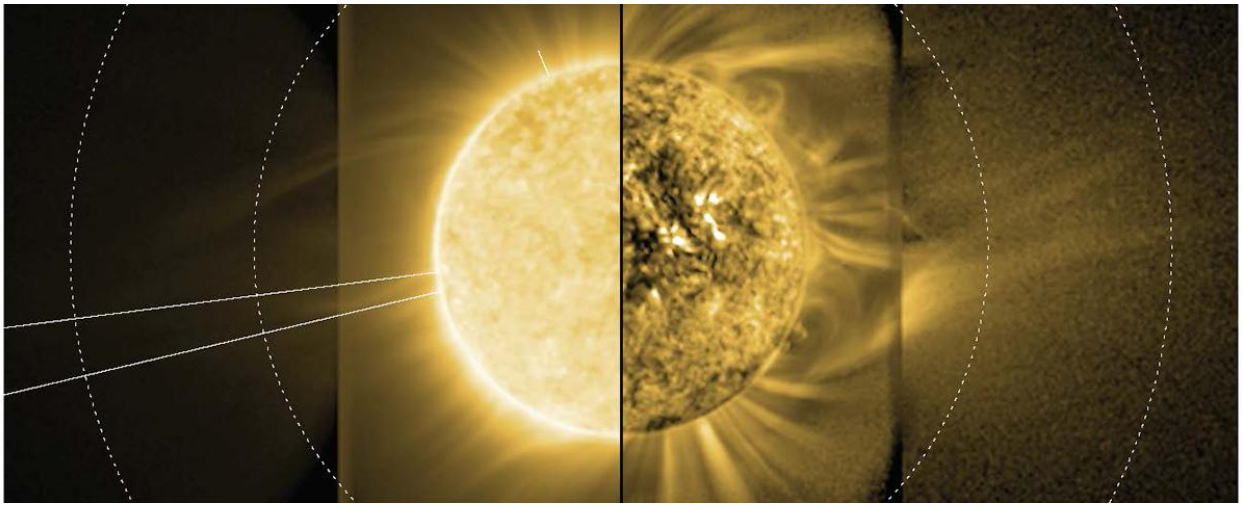
Section 3.B.2. Climate Science and Prediction
Intern Dylan Murphy measures the horizontal fuel continuity of a post-fire plant community in the Pumpernickel Valley, Nevada. Three years earlier, this was a completely different landscape of evergreen shrubs that burned in a large wildfire. The dead shrubs in the foreground survived the fire and subsequently died from drought stress because the invasive grasses that dominate the post-fire landscape changed the soil hydrology. Photo: Adam Mahood/CIRES

Section 3.B.3. Earth System Data Science, Stewardship, and Application
Matt Nolan prepares GPS for a transect of the McCall Glacier in the Arctic National Wildlife Refuge, to be used in a mass balance survey. Photo: Michael Stone/CIRES

Section 3.B.4. Regional Science and Applications
Scientists on the MOSAiC expedition in the Arctic begin to dismantle and move instruments from the melting ice during the fourth leg of the research mission in late 2020. Photo: Lianna Nixon/CIRES



Section 3.B.5. Scientific Outreach, Education, and Diversity
Students film an interview about water in the West as part of CIRES' Lens on Climate Change project. Left to right: Jacoby Sanchez (Des Moines, New Mexico), Jeff Lukas (CIRES scientist), Erik Morales (Anthony, New Mexico), Catherine Sullivan (Colorado Film School), Elliasar Soto (Monte Vista, Colorado). Photo: Katie Weeman/CIRES



Section 3.B.6. Space Weather Science and Prediction
CIRES researchers at NCEI used the GOES Solar Ultraviolet Imager to provide the first-ever movies of the Sun's elusive middle corona in extreme ultraviolet (EUV) light. These observations revealed the structure, temperature, and nature of EUV emissions from this region. Image: Dan Seaton/CIRES and NCEI

Section 3.B.7. Weather Research and Forecasting

A pair of landspout tornadoes whirl across rural Washington County, Colorado, on May 28, 2018. Photo: Jeff Duda/CIRES

Section 3.B.8. Science and Predictions to Support Ecosystem Research
Sea turtle tracks cross a beach in the early morning along the Outer Banks near Salvo, North Carolina, in August 2019. Photo: Kathy Bogan/CIRES