

 An official website of the United States government Here's how you know

[Proposals](#)

[Prepare & Submit Proposals](#)

[Demo Site: Prepare Proposals](#)

[Proposal Status](#)

[Reviews & Meetings](#)

[Reviews, Panels, and Other Meetings](#)

[Reviewing for the National Science Foundation](#)

[Awards & Reporting](#)

[Project Reports](#)

[Demo Site: Project Reports](#)

[Notifications & Requests](#)

[Award Documents](#)

[Supplemental Funding Requests](#)

[Demo Site: Supplemental Funding Requests](#)

[Continuing Grant Increments Reports](#)

[PAR Research Products](#)

[Fellowships & Opportunities](#)

[Graduate Research Fellowship Program \(GRFP\) \(Applicants, Fellows\)](#)

[Graduate Research Fellowship Program \(GRFP\) \(Officials\)](#)

[Education and Training Application \(ETAP\)](#)

[Manage Financials](#)

[ACM\\$ \(Award Cash Management Service\)](#)

[Program Income Reporting](#)

[Foreign Financial Disclosure Report \(FFDR\)](#)

[Individual Banking](#)

[Grant Post-Award Financial Contacts](#)

[Administration](#)

[User Management](#)

Preview of Award 2209711 - Annual Project Report

[Cover](#) |

[Accomplishments](#) |

[Products](#) |

[Participants/Organizations](#) |

[Impacts](#) |

[Changes/Problems](#)

Cover

Federal Agency and Organization Element to Which Report is Submitted:	4900
Federal Award or Other Identifying Number Assigned by Agency:	2209711
Project Title:	Frameworks: Large Scale Atmospheric Research Using an Integrated WRF Modeling, Visualization, and Verification Container Framework (I-WRF)
PD/PI Name:	Richard Knepper, Principal Investigator Sue E Haupt, Co-Principal Investigator Jared A Lee, Co-Principal Investigator Sara C Pryor, Co-Principal Investigator
Recipient Organization:	Cornell University
Project/Grant Period:	08/01/2022 - 07/31/2027
Reporting Period:	08/01/2025 - 07/31/2026
Submitting Official (if other than PD\PI):	N/A
Submission Date:	N/A
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	N/A

Accomplishments

* What are the major goals of the project?

The I-WRF project, part of the NSF's *Cyberinfrastructure for Sustained Scientific Innovation* (CSSI) program, aims to develop a containerized framework that streamlines the deployment of the Weather Research and Forecasting (WRF) model and the METplus verification tools. This framework is designed for use across diverse computing platforms—ranging from high-performance computing systems to cloud environments—with minimal installation overhead. The project supports three primary science use cases that examine the combined effects of climate variability on critical outcomes. Additionally, I-WRF enhances outreach by simplifying demonstrations, enabling hands-on training, and engaging potential future atmospheric scientists.

Major Goals

- Develop an integrated, containerized framework for the Weather Research and Forecasting (WRF) model, incorporating a new multi-node WRF container linked to an optimized Model Evaluation Tools (METplus) container with visualization capabilities to enhance research productivity.
- Enable multi-node simulations to support research-grade applications over large spatial domains at high resolution.
- Simplify usability to broaden accessibility, enabling researchers in fields such as environmental engineering, transportation, civil engineering, and urban planning to learn to use WRF, perform their own modeling activities, and interact easily with results.
- Establish a container framework that eliminates the need for users to individually configure and deploy all components. Containers will include entire environments and necessary workflows to support collaborative and complex tasks.
- Validate and test the integrated framework and container features on state-of-the-art parallel HPC and cloud platforms, using scalable use cases such as land use effects on weather.
- Utilize these containers as educational tools to introduce students to numerical atmospheric simulations and output evaluation through WRF and METplus tutorial and NSF NCAR training,
- Promote awareness of the I-WRF project and its framework capabilities to empower a broader cohort of next-generation researchers with practical tools for atmospheric science research.

These goals collectively aim to improve the accessibility, usability, and educational value of WRF and METplus tools, fostering innovation in atmospheric science research.

*** What was accomplished under these goals and objectives (you must provide information for at least one of the 4 categories below)?**

Major Activities: **Accomplishments**

We updated the I-WRF architecture to consolidate the Python environment into a single container by moving visualization tasks directly into the METplus validation container. This workflow saves user time by eliminating a dedicated visualization container and a second Python installation.

The first science use case focused on Land Use/Land Cover (LULC) modeling near urban areas. Modeling “what if” scenarios can better prepare U.S. cities for urban flooding events. To this end, we completed the Dallas-Fort Worth LULC use case (I-WRF v0.3) by creating a multi-node WRF container linked to a METplus container, which provides verification statistics and visualizations generated by our Python script. We performed short-duration (days), high-resolution (1.3 km) simulations with multiple perturbation experiments and physics settings. Results indicate that urban areas intensify deep convection but not uniformly, making mechanistic information difficult to extract from observations alone. A paired analysis of urban and equivalent rural areas also produced a mixed signal. This work is reported in Zhou X., Letson F., Crippa P. and Pryor S.C. (2024): Urban effects on precipitation from deep convective systems over Dallas-Fort Worth. *Journal of Geophysical Research* **129** 2023JD039972 doi: 10.1029/2023JD039972. Further simulation to examine generalizability were performed for the Boston to Washington, D.C. (BOS-WASH) corridor. This work is detailed in Xin Zhou and Sara C. Pryor’s paper, “Urban Effects on Precipitation from Deep Convection over the Northeastern United States in Current and Future Climate” and is currently under review. With our multi-node container linked to an enhanced METplus container, researchers can now use a larger domain or higher discretization to ask questions like, “What if we double or quadruple the size of the urban area?”

A second use case is examining changes in renewable energy resources over the Contiguous U.S. (CONUS). To accomplish this, we have run CORDEX-compliant regional climate simulations with the WRF model at 12-km grid spacing over all of North America, under both historical and projected future scenarios. One use of this data set is for studying renewable energy (RE) droughts, defined as shortfalls in wind or solar generation driven by weather variability. Development of this use case (I-WRF v0.4) is progressing. Understanding RE droughts is critical because while short-duration events lasting a few hours can be mitigated with battery storage or transmission, longer-duration droughts spanning one or more days require entirely new spatial and temporal mitigation strategies, especially events with coincident wind and solar droughts. Utility and grid operators want to mitigate these renewable energy droughts and use data to understand drought patterns. Open questions regarding renewable energy droughts include: Does wind plus solar help? Where are the gaps? What spatial scale is needed to mitigate droughts? What time frames and storage are needed to mitigate droughts? Will over-deploying renewables mitigate droughts?

Initial research to evaluate the I-WRF simulations and compute possible changes in the magnitude/seasonality of wind-generated electricity production used a subset of 20 years of historical and future simulations and was performed during the MEng degree of Patrick O’Connor by post-processing the hourly wind speeds through wind turbine power curves for each of the > 80,000 wind turbines currently operating in the contiguous U.S. Results suggest high fidelity relative to observed power generation in

different regions of the U.S and relative stability of power production in the ERCOT power grid (Texas). Patrick's thesis is "Projections of wind and solar PV power production under a changing climate."

To model these phenomena, we developed Python scripts leveraging the *windpowerlib* and *pvlib* packages to calculate estimated capacity factors (CF) for both wind and solar assets at every grid point and hour within the NA-CORDEX dataset, resulting in 46TB of output for 96 variables at various temporal resolutions. We built a database of 40 years historical data and currently 35 years of future data to study these renewable energy droughts. Results will be globally available via NCAR's Geoscience Data Exchange (GDEX) and possibly the Earth Science Grid Federation (ESGF). Currently, our team is identifying and correcting metadata and CF compliance issues within the WRF NA-CORDEX files to ensure data integrity. Our team is also using a capability of METplus called MODE or Method of Object-Based Diagnostic Evaluation. It defines "objects" and characteristics of them such as the centroid location, axis angle, object area, and intensity, and can be used to compare climatological distributions of selected object attributes. We will be calculating the rolling averages of wind and solar capacity so we can look at intensity, given duration.

New research has recently been completed and will be presented at the European Storms conference (TUDelft) that examines possible changes in extreme operating conditions. I-WRF simulations for nearly 500,000 grid cells have been used to derive 50-year return period extreme wind speeds for 35 years of historical and future using a suite of GEV distributions and to propose a new approach to optimal setting of wind speed threshold for peak-over-threshold based analyses.

Another RE study that we have prepared for demonstration using the dataset involves a specific use case domain and time frame featuring a dense cloud shield over southeastern New York with strong winds moving into western New York. Weather observations have been provided by New York State (NYS) Mesonet. We are configuring our METplus container to verify simulated 100-meter wind speeds against empirical data from 17 NYS Mesonet profiler stations, and global horizontal irradiance from 127 NYS Mesonet standard network stations. Deployment scripts from our previous Hurricane Matthew Demo (I-WRF v0.1/v0.2) are being adapted to successfully run the WRF and METplus/visualization containers.

The final science use case focuses on changes in air quality over the Northeast U.S. using WRF-Chem. WRF-Chem has traditionally been notably more difficult to use, due to the additional chemical input datasets required; only a handful of users apply it well. To support our Urban Air Quality (AQ) use case (I-WRF v0.5) and improve WRF-Chem accessibility, we built and tested a Docker container of WRF-Chem on Jetstream2 and Red Cloud, an on-premise cloud service at Cornell. We also containerized an initial demo of WRF-Chem using Apptainer and tested it on Derecho and finalized our domain configuration (12/4-km domains over the eastern U.S).

A primary goal of this use case is to democratize access to WRF-Chem, which has traditionally been limited to a small number of researchers. Improving its accessibility is vital for analyzing whether global climate warming leads to increased stagnation and precursor emissions. We are particularly interested in what impacts interannual variability and trends will have on urban AQ in the Northeast. Next steps include identifying and acquiring air quality observations, as well as assessing periods of extreme aerosol optical depth and near-surface fine particulate matter (PM2.5). This will result in detailed simulations of the interplay between emission changes, LULC change, and climate evolution.

Preparation for the I-WRF v1.0 public release is in progress. The upcoming release will include all developed use case demos, customization capabilities for configurations like the Hurricane Matthew use case, guided user exercises with documentation, container source files, and guidance to help users build their own containers.

Specific Objectives:

Significant Results:

Key outcomes or
Other achievements:

*** What opportunities for training and professional development has the project provided?**

The I-WRF project team provided professional development and mentoring to two postdoctoral fellows, a master's student, and a high school student. Postdoctoral fellow Xin Zhou participated in software engineering activities and team meetings, gaining valuable experience in research methodologies, scientific writing, and professional communication. Zhou also presented at conferences and authored several publications.

Yasir Latif, who is a Schmidt Foundation postdoctoral fellow, is using I-WRF NA-CORDEX output to build and test AI-based climate emulators for seasonal precipitation forecasts over different coherent regions of North America.

Patrick O'Connor, a Master of Engineering (MEng) student at Cornell, developed a novel methodology to evaluate wind turbine electricity-generation projections based on output from the I-WRF simulations.

Additionally, Kevin Diao, a Bronx High School of Science student mentored by PI Rich Knepper, developed a Convolutional Neural Network model for wildfire detection using perturbed WRF-Fire tutorial data to create a synthetic data set. Diao is currently assessing weather and conflict impacts on shipping lanes. Seeking to expand its educational impact, the I-WRF team is actively pursuing new opportunities to collaborate with undergraduate students.

While the Weather Research and Forecasting (WRF) model is highly popular with over 30,000 users, about half of the students and early career professionals participating in WRF tutorials report difficulties configuring the model for their specific platforms. Compiling WRF requires navigating multiple compiler frameworks, building required libraries with the selected WRF compiler, and managing a wide range of configuration options. Users must also learn where to obtain data for initial and lateral boundary conditions (ICs/LBCs), source observations for verification, and locate visualization tools configured to ingest WRF output. Our ultimate education goal is to make WRF more usable for other scientists and to provide an on ramp for students who would like to use WRF.

The I-WRF project aims to smooth the learning curve for inexperienced users, helping students learn how to configure and run these complex models. I-WRF integrates the WRF container with a METplus container, offering sample visualization scripts and practical demos.

Our initial container development example, Hurricane Matthew, demonstrated how instructors can quickly introduce students to WRF. Following a brief tutorial, students successfully worked through the example independently. They specifically praised the step-by-step documentation for being easy to follow.

Recently, high school student Diao successfully completed the tutorial independently as well. This milestone further validates our containers as a highly effective educational tool for introducing students to WRF.

*** Have the results been disseminated to communities of interest? If so, please provide details.**

Outreach during this reporting period included four invited presentations: "I-WRF North American Regional Climate Simulations for Solar and Wind Energy in a Changing Climate" and "Investigating Renewable Energy Drought Potential over the U.S." at the *2026 American Meteorological Society Annual Meeting* (Houston, TX); "Dunkelflaute and Solar Drought Potential" at the *2026 ESIG Forecasting and Meteorology in Power Systems Workshop* (Denver, CO); and "Historical and Future Wind Extremes over North America" at the *2026 European Windstorm Workshop* (Delft, Netherlands). We featured I-WRF at the *2025 NSF CSSI/CyberTraining/SCIFE PI Meeting* poster session (Denver, CO) and at *SC25* (St Louis, MO). Additionally, the article "Wind droughts threaten energy reliability" was published in *Nature*

Climate Change and our “Urban effects precipitation from deep convection over the northeastern United States in current and future climates” paper is currently in review.

*** What do you plan to do during the next reporting period to accomplish the goals?**

Our project’s No-Cost Extension (NCE) is approved, extending our timeline through July 2027 to complete all deliverables using existing funds. This extra time allows us to run long-term NA-CORDEX climate simulations on the high-demand Derecho system, finalize the containerization of WRF-Chem, carry out the Air Quality use case research with the containerized WRF-Chem, and expand team participation to include Cornell Master of Engineering or undergraduate students and a postdoctoral researcher.

We will present our findings at major venues, submitting abstracts to the 2027 American Meteorological Society (AMS) Annual Meeting and the CANOPIE HPC Workshop at SC26, while concurrently preparing several peer-reviewed manuscripts for atmospheric and computational journals.

Major technical milestones for the upcoming period focus on software releases, beginning with the deployment of the I-WRF v0.4 renewable energy (RE) drought demo. This release features METplus container verification of WRF simulations against observations from New York State Mesonet (127 weather stations spanning 62 counties), complemented by newly developed WRF visualization scripts. To ensure broad accessibility, we will publish dedicated METplus deployment instructions for multiple platforms, including Jetstream2, Red Cloud, and Derecho.

The technical workflow for the RE drought use case will proceed in five structured phases: (1) we will finish identifying and correcting metadata and other Climate and Forecast (CF) Convention compliance issues within the WRF NA-CORDEX files; (2) we will update the METplus code base to ensure seamless ingestion and processing of the CORDEX-formatted files; (3) the team will calculate rolling averages for wind and solar capacity factors across various temporal durations, such as 1, 3, 5, and 7 days, to evaluate Intensity-Given-Durations; (4) we will build comprehensive climatologies of object attributes—specifically individual object area, total object area, and 50th and 90th percentile intensities—across the major power interconnects, including the Western Interconnection (WIC), the Eastern Interconnection (EIC), the Quebec Interconnection (QIC), and ERCOT; and (5) we will conduct rigorous statistical comparisons matching historical climate WRF data against ERA5, bias-corrected ERA5 (ERA5BC), and future climate WRF projections.

Following this, the project team will complete and release the I-WRF v0.5 air quality change demo, which includes observations for METplus and tailored visualization scripts. The air quality workflow involves completing robust testing of the WRF-Chem container on the Derecho system, demonstrating container utility across both historical and projected future air quality scenarios, and analyzing these outputs to quantify long-term projected changes. Executing this use case will require identifying and obtaining targeted atmospheric observations for the METplus container demo and adapting existing WRF visualization scripts accordingly.

The final phase culminates in the completion and public release of I-WRF v1.0, featuring user customization capabilities. We will integrate step-by-step user exercises detailing how to modify WRF physics options, configure METplus metrics, alter statistical outputs, and customize sample visualizations. This release will enable users to select custom simulation dates, automatically triggering the retrieval of required WRF Initial Conditions (ICs), Lateral Boundary Conditions (LBCs), and corresponding validation observations, while offering some level of guided instructions to help users design their own custom containers.

Ultimately, the finalized "Understanding Renewable Energy Droughts" and "Air Quality in an Evolving Climate" use cases will be deployed for broader atmospheric research and student communities. These containers will serve as valuable outreach tools to support live tutorials and interactive demonstrations, while concurrently supporting impactful science. Upon completing a final quality assurance check of the how-to documentation within the I-WRF User Guide, we will deliver, record, and post an NSF NCAR webinar on I-WRF. This will be led by Jared Lee, George McCabe, and Rich Knepper, with direct use case support from Sara C. Pryor, Xin Zhou, and Sue Ellen Haupt.

Planning & Oversight

The technical and use case plans for the upcoming project year were reviewed at the I-WRF Advisory Board meeting on May 11, 2026. James Wilczak, an expert in renewable energy and retired NOAA researcher, and Rebecca Barthelmie, a Cornell professor and co-chief editor of the journal *Wind Energy*, are valuable new additions to the I-WRF research team.

All work tasks and sub issues continue to be carefully assigned, monitored, and tracked using the I-WRF development board.

Documentation & Access

We updated our User Guide instructions and demos based on user feedback. Documentation is hosted on Read the Docs. Our demo containers are stored and updated on Docker Hub across three repositories, as well as at NCAR. The I-WRF METplus repository hosts the METplus container, which includes all the METplus software and analysis tools for generating statistical plots. This repository also features a Python package for creating plots of the WRF output itself, alongside METplus wrappers, which are Python tools used to orchestrate these components. Lastly, new data volumes containing the input data used in our use cases were added to the I-WRF data repository.

- I-WRF GitHub Repository: <https://github.com/NCAR/i-wrf>
- Overview website: <https://i-wrf.org/>
- User's Guide: <https://i-wrf.readthedocs.io>
- WRF Container with software required to run WRF: <https://hub.docker.com/repository/docker/ncar/iwrf>
- METplus Container: with METplus wrappers, MET C++ executables, METplus data analysis plotting tools, and the WRF-Python package: <https://hub.docker.com/repository/docker/ncar/iwrf-metplus>
- Data Volumes used to run the I-WRF use cases: <https://hub.docker.com/repository/docker/ncar/iwrf-data>
- Hurricane Matthew demo: https://i-wrf.readthedocs.io/en/latest/Users_Guide/use-cases/matthew.html
- Land Use/Land Cover demo: https://i-wrf.readthedocs.io/en/latest/Users_Guide/use-cases/lulc.html

Products

Books

Book Chapters

Inventions

Journals or Juried Conference Papers

View all journal articles and conference papers currently available in the [NSF Public Access Repository](#) for this award.

The results in the NSF Public Access Repository will include a comprehensive listing of all journal articles and conference papers recorded to date that are associated with this award.

Zhou, Xin and Letson, Fred and Crippa, Paola and Pryor, Sara C. (2024). Urban Effect on Precipitation and Deep Convective Systems Over Dallas-Fort Worth. *Journal of Geophysical Research: Atmospheres*. 129 (10) . Status = Added in NSF-PAR [PAR ID: 10527446](#)

Federal Government's License = Acknowledged. (Completed by Knepper, Richard on 07/29/2024) [Full text](#) [Citation details](#)

Knepper, Richard and Pryor, Sara and Wineholt, Bennett and Bukovsky, Melissa and Lee, Jared and Zhou, Xin. (2023). The I-WRF Framework: Containerized Weather Modeling, Validation, and Verification. . 206 to 210. Status = Added in NSF-PAR [PAR ID: 10527497](#)

Federal Government's License = Acknowledged. (Completed by Knepper, Richard on 07/29/2024) [Full text](#) [Citation details](#)

Haupt, Sue Ellen. (2025). Wind droughts threaten energy reliability. *Nature Climate Change*. 15 (8) 814 to 815. Status = Added in NSF-PAR [PAR ID: 10691198](#) Type: Version of Record

Federal Government's License = Acknowledged. (Completed by Knepper, Richard on 06/17/2026) [Full text](#) [Citation details](#)

Xin Zhou and Sara C. Pryor Urban Effects on Precipitation from Deep Convection over the Northeastern United States in Current and Future Climates Journal of Geophysical Research: Atmospheres 2025 Acknowledgement of Fed. Support: Yes. Status = UNDER_REVIEW.

Licenses

Other Conference Presentations / Papers

Jared A. Lee, Amanda R. Siems-Anderson, Sue Ellen Haupt, James M. Wilczak, Sara C. Pryor, Xin Zhou, and Rebecca J. Barthelmie (2026). *Dunkelflaute and Solar Drought Potential in North America*. ESIG 2026 Forecasting and Meteorology Power Systems Workshop. Denver, CO. Status = AWAITING_PUBLICATION; Acknowledgement of Federal Support = Yes

Xin Zhou, Sara C. Pryor, Jared A. Lee, Sue Ellen Haupt, Jimmy Dudhia, and Richard Knepper (2026). *I-WRF North American Regional Climate Simulations for Solar and Wind Energy in a Changing Climate and More*. American Meteorological Society Annual Meeting. Houston, TX. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Jared A. Lee, Amanda R. Siems-Anderson, Sue Ellen Haupt, James M. Wilczak, Sara C. Pryor, Xin Zhou, and Rebecca J. Barthelmie (2026). *Investigating Renewable Energy Drought Potential over the U.S.*. American Meteorological Society Annual Meeting. Houston, TX. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Other Products

View all datasets currently available in the [NSF Public Access Repository](#) for this award.

The results in the NSF Public Access Repository will include a comprehensive listing of all datasets recorded to date that are associated with this award.

View all workshop reports currently available in the [NSF Public Access Repository](#) for this award.

The results in the NSF Public Access Repository will include a comprehensive listing of all workshop report publications recorded to date that are associated with this award.

Other Publications

Patent Applications

Technologies or Techniques

WRF-Chem was containerized using Apptainer for Derecho, and Docker for Jetstream2 and Red Cloud. Additionally, the team completed I-WRF v0.3, a Land Use/Land Cover (LULC) use case: https://i-wrf.readthedocs.io/en/latest/Users_Guide/use-cases/lulc.html

Thesis/Dissertations

Websites or Other Internet Sites

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Knepper, Richard	PD/PI	1
Haupt, Sue	Co PD/PI	1
Lee, Jared	Co PD/PI	2
Pryor, Sara	Co PD/PI	1

Full details of individuals who have worked on the project:

Richard Knepper**Email:** rich.knepper@cornell.edu**Most Senior Project Role:** PD/PI**Nearest Person Month Worked:** 1**Contribution to the Project:** Programmatic oversight of the I-WRF project ensuring deliverables outlined in the proposal are met.**Funding Support:** No funding support from other projects was used for this award.**Change in active other support:** No**International Collaboration:** No**International Travel:** No

Sue E Haupt**Email:** haupt@ucar.edu**Most Senior Project Role:** Co PD/PI**Nearest Person Month Worked:** 1**Contribution to the Project:** Oversees all science use cases and is co-developer of the Renewable Energy use case.**Funding Support:** No funding from other projects used for this award.**Change in active other support:** No**International Collaboration:** No**International Travel:** No

Jared A Lee**Email:** jaredlee@ucar.edu**Most Senior Project Role:** Co PD/PI**Nearest Person Month Worked:** 2**Contribution to the Project:** Coordinates the operations of the NCAR technical team and is the general project manager for WRF development.**Funding Support:** No funding support from other projects was used for this award.**Change in active other support:** No**International Collaboration:** No**International Travel:** No

Sara C Pryor**Email:** sp2279@cornell.edu**Most Senior Project Role:** Co PD/PI**Nearest Person Month Worked:** 1**Contribution to the Project:** Scientific guidance, management of a postdoctoral researchers, and interface with the WRF user community among researchers to provide information about the I-WRF Framework for adopters and to perform analyses of I-WRF simulation output.**Funding Support:** No funding support from other projects used for this award.

Change in active other support: No

International Collaboration: No

International Travel: No

What other organizations have been involved as partners?

Nothing to report.

Were other collaborators or contacts involved? If so, please provide details.

Nothing to report

Impacts

What is the impact on the development of the principal discipline(s) of the project?

The project team is developing and implementing an integrated multi-container framework for the Weather Research and Forecasting (WRF) model. This initiative marks a significant milestone by enabling multi-node containerized simulations equipped with verification and visualization capabilities.

This advancement streamlines the utilization of WRF for atmospheric researchers and students, democratizing access across various platforms, including desktops, cloud infrastructures, and supercomputers. The urgency for enhanced climate modeling—underscored by the NSF Engineering Visioning Alliance Forum—highlights the critical need for comprehensive simulations to bolster climate resilience within the U.S. economy. By providing a portable, scalable framework and conducting focused science use case studies, this project empowers a broader community of researchers to conduct diverse simulations. This expanded engagement is essential for delivering actionable insights to stakeholders, exploring model uncertainties, and driving fundamental advancements in climate science.

What is the impact on other disciplines?

I-WRF's integrated capabilities and user-friendly design empower researchers across diverse fields to independently conduct modeling activities and seamlessly interact with their findings. By employing a containerized framework, the system lowers technical barriers for early career scientists in various disciplines, facilitating easier adoption of numerical simulations.

This accessibility eliminates the prerequisite of Linux expertise previously needed to engage with the WRF system, democratizing access for new users. Wrappers and tools developed by I-WRF also benefit software communities, such as researchers who use METplus. The team contributed the containerized Hurricane Matthew demo to the METplus Repository, which features use case examples. Additionally, a Land Use/Land Cover container has been completed.

Furthermore, standardized software environments facilitate reproducible results, fostering collaboration among distributed domain experts and minimizing outcome variability due to differing computing architectures. Ultimately, these containerized systems promote science excellence across disciplines while increasing usage.

Additionally, the project has joined NA-CORDEX. Simulation results will be globally available via NCAR's Geoscience Data Exchange (GDEX) and possibly the Earth Science Grid Federation (ESGF).

What is the impact on the development of human resources?

The project actively advances human resources by immersing postdocs and students in advanced technologies and complex research challenges. These efforts empower emerging researchers in atmospheric sciences and other disciplines by promoting best practices in compilation, configuration, and cyberinfrastructure deployment.

What was the impact on teaching and educational experiences?

Outreach by NCAR will feature the delivery, recording, and promotion of an I-WRF educational webinar. To introduce

students to WRF, container demonstrations will be readily available to colleges and universities. Our container approach to education is designed to overcome the limitations of current WRF tutorials, during which ~50% of students cannot compile the software for their platforms or experience severe difficulty doing so.

What is the impact on physical resources that form infrastructure?

The project focuses on enhancing the portability of WRF across diverse cyberinfrastructures. Utilizing pre-compiled and tested Docker images, students can streamline setup times on desktops and cloud deployments. For researchers, productivity gains on HPC and cloud platforms may be achieved through tailored implementations for launching WRF jobs on different platforms. Our primary focus includes HPC environments supporting Apptainer containers and cloud systems and desktops compatible with Docker container runtimes. While our approach ensures efficient performance through optimized library availability and minimal runtime overhead, it acknowledges potential limitations in supporting specialized hardware or constrained container environments.

What is the impact on institutional resources that form infrastructure?

Enhancing the portability of WRF containers expands institutional options for executing WRF simulations. With improved WRF training, institutions can reduce the resources required to support researchers using WRF. This advancement enables users to initiate multi-node WRF simulations independently, thereby decreasing reliance on institutional IT personnel. Furthermore, this flexible containerized workflow empowers researchers to leverage a wider array of cyberinfrastructure resources, which diminishes the ongoing administrative demands on CI providers.

What is the impact on information resources that form infrastructure?

To maximize research impact and reach a global audience, I-WRF use case scripts, build files, and data configurations will be distributed alongside sample datasets. Aligning this work with the Coordinating Regional Climate Downscaling Experiment (CORDEX)—operating under the World Climate Research Programme (WCRP)—and adopting its standard convention will significantly amplify the project's reach. This integration enables seamless provisioning of climate projections to an expansive community, tapping into a highly recognized framework that boasts over 31,000 citations on Google Scholar.

What is the impact on technology transfer?

I-WRF's open-source technology eliminates traditional licensing negotiations and patent applications, shifting the impact of technology transfer toward rapid, barrier-free adoption and community-driven innovation.

What is the impact on society beyond science and technology?

The I-WRF project advances critical atmospheric research affecting U.S. citizens by executing multi-node containerized simulations of extreme weather, energy production, and air quality. It democratizes access for students and early career scientists while exploring how wind, solar, and land use impact sustainable energy systems.

What percentage of the award's budget was spent in a foreign country?

Nothing to report.

Changes/Problems

Changes in approach and reason for change

Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them

Nothing to report.

Changes that have a significant impact on expenditures

Nothing to report.

Significant changes in use or care of human subjects

Nothing to report.

Significant changes in use or care of vertebrate animals

Nothing to report.

Significant changes in use or care of biohazards

Nothing to report.

Change in primary performance site location

Nothing to report.