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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 - 07/31/2026
Reporting Period:	08/01/2024 - 07/31/2025
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, an optimized Model Evaluation Tools (METplus) container, and 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, agriculture, and urban planning to 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 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 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 tutorials 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

Visualization containers supporting the Hurricane Matthew use case were developed, documented, and user tested.
Containers that replicate the versions of WRF and WPS used in the Land Use/Land Cover

(LULC) study—*Urban Effects on Precipitation & Deep Convective Systems Over Dallas–Fort Worth* (Zhou, Letson, Crippa, & Pryor, https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023JD039972)—were added via pull request NCAR/i-wrf#72 (https://github.com/NCAR/i-wrf/pull/72).
A container for running METplus verification and visualization components was also created and made publicly available on DockerHub (https://hub.docker.com/r/ncar/iwrf/tags). Input data for the METplus/Visualization portion of the LULC use case were uploaded. These include Docker data volumes containing radar observation data and WRF output, allowing users to bypass the timely modified WRF runs. Each input dataset is available in two formats—one for Docker and one for Apptainer—to ensure compatibility.
A Python script was developed to convert radar observations into a format readable by MET verification tools. Enhancements were made to MET to allow direct reading of WRF output natively, eliminating the need for an ingest script. The METplus configuration file manages both verification and plotting tasks. The MET Point-Stat tool uses point observations to verify gridded WRF, while METplus Analysis tools, including METreformat and METplotpy, generates visualizations. A Python script by Jared Lee (NSF NCAR) is also invoked by METplus to plot WRF output.
Xin Zhou and Sara C. Pryor (Cornell) are undertaking simulations for science use case #2 on Derecho. Specific science objectives have been developed by them and shared with the NSF NCAR science team (Jared Lee, Sue Ellen Haupt, and Amanda Siems-Anderson) who are working to integrate their analysis plans. Jared will also develop a corresponding I-WRF demo use case. This and other use cases will serve as exemplars for the broader research community.
Staff have been identified to build a WRF-Chem container for I-WRF. Victor Weeks and David Hahn (NSF NCAR) plan to complete this work by September 30, 2025. Based on that configuration and analysis of runs, an I-WRF demo use case will be created.
Metrics for DockerHub pulls and GitHub pull requests have not yet been tracked, as development of versions 0.4.0 and 0.5.0 has not formally started. The revised target completion date for those versions is March and April 2026.
Project outreach included four conference presentations, a panel discussion, and an interactive tutorial delivered at:

- MS-CC Workshop on Campus Technology, Cybersecurity & Research Computing Support
- 2024 American Geophysical Union Fall Meeting
- 8th International Conference on Energy & Meteorology
- 2025 Energy Systems Integration Group Forecasting & Markets Workshop

Two educational videos—*Introduction to I-WRF Containers* and *I-WRF Workshop Introduction*—have accumulated a combined 335 views.
Additionally, a paper by Xin Zhou and Sara C. Pryor, *Urban Effects on Precipitation from Deep Convection over the Northeastern United States in Current and Future Climates*, is currently under review by the *Journal of Geophysical Research*.
Project progress is tracked at https://github.com/NCAR/i-wrf.

Specific Objectives:

Significant Results:

Key outcomes or
Other achievements:

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

I-WRF User Guides for running the Hurricane Matthew use case on multiple platforms are available at: https://i-wrf.readthedocs.io/en/latest/Users_Guide/matthew_usecase.html#matthewusecase.
A group of undergraduate and graduate students followed the Hurricane Matthew tutorial on Jetstream2 during an MS-CC Workshop at Alabama A&M University using the step-by-step instructions in our User Guide: https://i-wrf.readthedocs.io/en/latest/Users_Guide/matthewjetstream.html#matthewjetstream
A postdoctoral fellow participated in the project's software engineering activities and team meetings, gaining valuable experience in research methodologies, scientific writing, and professional communication.

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

Conference Presentations
Lee, J. A., 2024: Introduction to CI-Enabled Climate Science Research and Student Opportunities at NSF NCAR, *MS-CC Workshop: Campus Technology, Cybersecurity, & Research Computing Support*, Alabama A&M University, Huntsville, AL, 29–30 Oct 2024. https://ms-cc.org/ms-cc-campus-technology-cybersecurity-research-computing-support-workshop/
Zhou X., Letson F., Crippa P., Bukovsky M. and Pryor S.C., 2024: Influence of Urbanization on Deep Convection in Different Climates. *American Geophysical Union Fall Meeting 2024*, Washington, DC, Dec. 2004. https://agu.confex.com/agu/agu24/meetingapp.cgi/Paper/1639438
Haupt, S.E., 2025: What's Needed for Best Practice Forecasts? *Energy Systems Integration Group Forecasting & Markets Workshop*,

Nashville, TN, 24 June 2025. https://www.esig.energy/2025-forecasting-markets-workshop-agenda/
Lee, J. A., A. Siems-Anderson, S. E. Haupt, J. M. Wilczak, X. Zhou, S. C. Pryor, and R. J. Barthelmie, 2025: Exploring Renewable Energy Drought Potential over CONUS. *8th International Conference on Energy & Meteorology*, Padova, Italy, World Energy & Meteorology Council, 3 Jun 2025. https://i-wrf.org/about/Lee-ICEM-20250603.pdf

Panel

Lee, J. A., 2024: "Career Conversations Panel: Data-Intensive Climate Science." *MS-CC Workshop: Campus Technology, Cybersecurity, & Research Computing Support*, Alabama A&M University, Huntsville, AL, 29–30 Oct 2024, https://ms-cc.org/ms-cc-campus-technology-cybersecurity-research-computing-support-workshop/

Publication

Zhou X. and S.C. Pryor, 2025: Urban Effects on Precipitation from Deep Convection over the Northeastern United States in Current and Future Climates. *Journal of Geophysical Research* in review.

Tutorial

Lee, J. A. and B. Trumbore, 2024: I-WRF Interactive Tutorial, *MS-CC Workshop: Campus Technology, Cybersecurity, & Research Computing Support*, Alabama A&M University, Huntsville, AL, 29–30 Oct 2024, Presentation: https://i-wrf.org/about/Lee-MS-CC-I-WRF-Tutorial-20241029.pdf; Demo: https://i-wrf.readthedocs.io/en/latest/Users_Guide/matthewjetstream.html#matthewjetstream)

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

Plans/Target Completion Dates

August 29, 2025
- Complete the v0.3.0 containers and documentation, including sufficient testing to make any necessary revisions

Sept. 30, 2025
- Build the WRF-Chem container for I-WRF (V. Weeks, D. Hahn)
- Plan and start running the configuration of the WRF-Chem simulation in Fall 2025 (J. A. Lee, S.C. Pryor)

Oct. 4, 2025
- Begin LULC use case runs (S.C. Pryor, G. McCabe)
- Complete enough runs by **December 6**, to provide the technical team with feedback needed to revise the v.0.3.0 container and documentation

Oct. 31, 2025
- Complete the 12-km WRF regional climate dataset (X. Zhou)
- Refine the scientific analysis plan for this dataset (X. Zhou, S.C. Pryor, J. A. Lee, S.E. Haupt)
- Develop a suitable I-WRF demo use case (J.A. Lee)

Dec. 6, 2025
- Document in the I-WRF User Guide and begin end-to-end runs for the climate impacts on energy production use case (S.E. Haupt, G. McCabe)

Feb. 7, 2026
- Complete enough energy production use case runs to provide technical team feedback they need to create the v.0.4.0 container and documentation

Feb. 28, 2026
- Complete development of an I-WRF-Chem demo use case (J.A. Lee, S.C. Pryor)

March 31, 2026
- Begin Air Quality in the Northeastern U.S. use case runs (J.A. Lee, G. McCabe)
- Complete sufficient runs by **April 21** to support revision of the v.0.5.0 container and documentation by the technical team

May 1, 2026
- Public release of I-WRF v1.0.0 with all documentation finalized and DockerHub images available (G. McCabe)
- Commence tracking DockerHub Pulls, and External GitHub Pull Requests/Merged Requests and report stats **July 5** (G. McCabe)
- Deliver/record/post an NSF NCAR Webinar on I-WRF (J.A. Lee, G. McCabe, R. Knepper lead with use case support from S.C. Pryor, X. Zhou, S.E. Haupt). The I-WRF Webinar will be in lieu of a text-based Virtual Workshop which is not required due to extensive how-to documentation in the User Guide.

Planning & Oversight

The technical plan for the upcoming project year will be reviewed at the I-WRF Advisory Board meeting on **August 20, 2025**. Input will be solicited on implementation strategies and ways to expand project impact and visibility.

Documentation & Access

All container capabilities and workflows will continue to be documented in the I-WRF User Guide, available via the I-WRF GitHub repository. Updated I-WRF container images will be published to DockerHub.

Products

Books

Book Chapters

Inventions

Journals or Juried Conference Papers

View all journal publications 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 publications recorded to date that are associated with this award.

Crippa, Paola and Letson, Fred and Pryor, Sara C and Zhou, Xin. (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

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

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

Federal Government's License = Acknowledged. (Completed by Knepper, Richard on 07/29/2024) 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 (2024). *Career Conversations Panel: Data-Intensive Climate Science*. MS-CC Workshop: Campus Technology, Cybersecurity, & Research Computing Support. Huntsville, AL. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Jared A. Lee, Amanda Siems-Anderson, Sue Ellen Haupt, James M. Wilczak, Xin Zhou, Sara C. Pryor, and Rebecca J. Barthelmie (2025). *Exploring Renewable Energy Drought Potential over CONUS*. 18th International Conference on Energy & Meteorology. Padova, Italy. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Jared A. Lee and Ben Trumbore (2024). *I-WRF Interactive Tutorial*. MS-CC Workshop: Campus Technology, Cybersecurity, & Research Computing Support. Huntsville, AL. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Xin Zhou, Fred Letson, Paola Crippa, Melissa Bukovsky, and Sara C. Pryor (2024). *Influence of Urbanization on Deep Convection in Different Climates*. American Geophysical Union Fall Meeting. Washington, DC. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Jared A. Lee (2024). *Introduction to CI-Enabled Climate Science Research and Student Opportunities at NSF NCAR*. MS-CC Workshop: Campus Technology, Cybersecurity, & Research Computing Support. Huntsville, AL. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Sue Ellen Haupt (2025). *What's Needed for Best Practice Forecasts?*. Energy Systems Integration Group Forecasting & Markets Workshop. Nashville, TN. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Other Products

Audio or Video Products *An "I-WRF Workshop Introduction" was presented and is now available on YouTube.*

Other Publications

Patent Applications

Technologies or Techniques

A container for running METplus verification and visualization components was created and made publicly available on

DockerHub (https://hub.docker.com/r/ncar/iwrf/tags).

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 on schedule.

Funding Support: No other funding support

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: N/A

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: N/A

Change in active other support: No

International Collaboration: No
International Travel: Yes, Italy - 0 years, 0 months, 3 days

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 post-doctoral researchers, and interface with the WRF user community among researchers to provide information about the I-WRF Framework for adopters.

Funding Support: N/A

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 actively developing, testing, and implementing an integrated multi-container framework for the WRF model. This initiative marks a significant milestone by enabling multi-node containerized simulations equipped with verification and visualization capabilities. This advancement aims to streamline the utilization of WRF for atmospheric researchers, democratizing access across various platforms—from desktops to cloud infrastructures and supercomputers.

The urgency for enhanced climate simulations is underscored by events like the NSF Engineering Visioning Alliance Forum. This forum highlighted the critical need for comprehensive simulations of future climate scenarios to bolster climate resilience within the U.S. economy. Our project addresses these imperatives through focused science case studies and importantly, it will empower a broader community of researchers to conduct diverse simulations. This broader engagement is essential for delivering actionable insights to stakeholders, exploring uncertainties, and driving fundamental advancements in climate science.

What is the impact on other disciplines?

I-WRF's integrated capabilities and user-friendly design will empower researchers across diverse fields to independently conduct modeling activities and seamlessly interact with their findings. By employing a containerized framework, the system lowers the barriers for early career scientists in various disciplines, facilitating easier adoption of numerical simulations and evaluation processes. This accessibility eliminates the prerequisite of Linux expertise previously needed to engage with the WRF system, thus democratizing access for new users to explore its capabilities.

Furthermore, the standardized software environments help to facilitate reproducible results, fostering collaboration among distributed domain experts and minimizing variability in outcomes due to different computing architectures. Ultimately, these containerized

systems promote excellence in science and engineering across disciplines while increasing usage.

What is the impact on the development of human resources?

The project nurtures postdocs and early career researchers by immersing them in both the technologies and research challenges involved. This initiative will support the cultivation of new scholars and technologists through training programs offered at NSF NCAR. These efforts will empower a greater number of emerging researchers in atmospheric science and promote best practices in compilation, configuration, and cyberinfrastructure deployment.

What was the impact on teaching and educational experiences?

NSF NCAR tutorials will offer I-WRF container options to enhance the training of a wider range of graduate students and early career researchers in the atmospheric sciences, thereby bolstering the science and engineering (S&E) workforce. The team also intends to draw from previous collaborations and establish direct partnerships to expose other institutions to I-WRF capabilities.

To further extend educational opportunities, we will develop/record/post an I-WRF Educational Webinar upon release of v.1.0.0.

What is the impact on physical resources that form infrastructure?

The I-WRF project focuses on enhancing the portability of the Weather Research and Forecasting (WRF) model across diverse cyberinfrastructures. Utilizing pre-compiled and tested Docker images, students can streamline setup times on desktops and small-scale cloud deployments. For researchers, productivity gains on HPC and cloud platforms will be achieved through tailored implementations for launching WRF jobs across different clusters and clouds.

To achieve this, we are adopting Python as the primary invocation layer. For cloud resources, we will employ Terraform Python CDKTF for resource provisioning scripts, while local desktop execution will utilize the Docker Engine Python interface, docker-py.

Our primary focus includes HPC environments supporting Apptainer containers and CPU-based cloud systems and desktops compatible with Docker container runtimes. This strategy aligns with current capabilities of WRF MPI Fortran code compilation, which is optimized for CPU architectures. 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 running WRF simulations. With improved training, institutions can reduce the resources required to support researchers using WRF. This advancement enables researchers to initiate multi-node WRF simulations independently, reducing reliance on institutional staff. The flexible containerized workflow allows researchers to leverage a wide range of cyberinfrastructure resources, with minimal demands on CI providers.

What is the impact on information resources that form infrastructure?

I-WRF use case scripts, build files, and related materials will be distributed alongside sample data and storage configurations.

What is the impact on technology transfer?

Since the technologies developed in this project are open source, there is no need for technology transfer licensing, patent applications, or similar processes.

What is the impact on society beyond science and technology?

The I-WRF project aims to advance significant research that directly affects the daily lives of U.S. citizens, agriculture, energy production, and public health. It will achieve this by facilitating the execution of extensive simulations and by enhancing accessibility to computational methods in atmospheric research for students.

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.