U.S. Department of Energy
Office of Science

APPLICATION/PROPOSAL COVER SHEET

THE ATTACHED APPLICATION/PROPOSAL IS FOR YOUR REVIEW & APPROPRIATE ACTION

INSTITUTION: Pacific Northwest National Laboratory (PNNL), Richland, WA

TYPE OF REQUEST: New

P.I.: Fan, Jiwen

DATE RECEIVED: 11/14/2016 1:15 PM

AWARD NO: N/A

SOLICITATION NO: LAB 16-1625

TITLE: Understanding Severe Thunderstorms in the Central United States

TOTAL NUMBER OF PAGES SUBMITTED: 46

ERROR LIST: N/A

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SOLICITATION INFORMATION

Solicitation Number:	LAB 16-1625: Early Career Research Program
Institution:	Pacific Northwest National Laboratory (PNNL), Richland, WA

PRINCIPAL INVESTIGATOR INFORMATION

Name:	Fan, Jiwen
Position/Title of PI:	Scientist
Phone Number:	N/A
Email Address:	jiwen.fan@pnnl.gov
Address:	PO BOX 999, Richland, WA 99352

PROJECT INFORMATION

Proposal Title:	Understanding Severe Thunderstorms in the Central United States	
Program Manager:	Joseph, Renu	
Proposal Type:	New	
Project Proposed Dates:	7/15/2017 - 7/14/2022	
Field Work Proposal Number(s) (if applicable):	*FWP Number:*	*Target Year:*
	70017	2017
Estimated Project Funding:	$2,500,000.00	

RESEARCH AND OTHER PROJECT RELATED INFORMATION

1. Are Human Subjects Involved?:	No
1a. If Yes, is the project exempt from Federal regulations?:	N/A
If Yes, appropriate exemption number:	N/A
If No, is the IRB review pending:	N/A
IRB Approval Date:	N/A
Human Subject Assurance Number:	N/A
2. Are vertibrate animals used:	No
2a. If Yes, is the IACUC review pending:	N/A
IACUC Approval Date:	N/A
Animal Welfare Assurance Number:	N/A

Project Summary

Understanding Severe Thunderstorms in the Central United States

Principal Investigator: Jiwen Fan, Pacific Northwest National Laboratory

Severe thunderstorms (STs) are an extreme form of storm clouds that produce large hail, damaging winds and/or tornadoes, and torrential rainfall. There is increasing concern about how these "deep convective" clouds are changing in occurrence and intensity. Earth system models (ESMs) are used to understand these ST systems, yet two significant problems persist with the previous research: (1) coarse resolution ESM simulations only account for the large-scale environments, thus ignoring the smaller storm-scale physical processes and how they feedback to the storm's dynamics; and, (2) there is a built-in assumption that the mechanisms controlling ST initiation will not significantly vary across different Earth system states. This research addresses the two issues by answering major overarching science questions: Q1. What are the significant interactions of storm dynamics with the specific environmental factors of land-surface, atmospheric particles, and extreme precipitation that affect ST occurrence and intensity? How do urbanization and wildfires affect ST characteristics over the central United States (CUS)? Q2. What are the overall effects of the compounding extremes on ST characteristics over the CUS? The objective of this research is to improve the foundational understanding of key physical processes that impact ST characteristics. First, the research will focus on of the impacts of urbanization and wildfires, as well as explore the feedback of extreme soil moisture resulting from extreme precipitation to the subsequent ST formation and intensity. Second, the research will provide a comprehensive performance assessment of ST characteristics in a new regionally refined ESM with advanced formulations of dynamics, urbanization, and wildfire. Third, this research will provide a robust understanding of how ST characteristics change in the CUS by considering the compounding extreme events of droughts, extreme precipitation/flash floods, and urbanization. The grand deliverable of this research is advanced understanding of ST activities in the past and future by investigating previously unexplored links between STs and the evolving Earth system, which is affected by wildfires and urbanization. The research will fill a significant gap in understanding the important physical and dynamical interactions involving microphysics, atmospheric particles, the land surface, and precipitation that affect ST characteristics.

Budget Period: 1 Duration: 12 months	DOE Funded Person-mos.			Funds Requested ($) (Salary+Fringe)
	CAL	ACAD	SUMR	
A. Senior Personnel: PI/PO, Co-PI's, Faculty and Other Senior Associates **Total Senior Personnel (1-8)**				86,975.09
1. Fan, Jiwen	6	0	0	86,975.09
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9. Others (See Attachment for Details)				0.00
B. Other Personnel (Number in Brackets) **Total Other Personnel**				161,195.33
(2) Post Doctoral Associates	24			159,431.88
(0) Graduate Students				0.00
(0) Undergraduate Students				0.00
(1) Secretarial / Clerical	0.1			437.03
(1) Project Coordinator	0.2			1,326.42
Total Personnel Costs **Total Salaries and Wages (A+B)**				248,170.42
C. Permanent Equipment **Total Permanent Equipment**				66,500.00
PNNL Institutional Computing: 66,500.00;				
D. Travel **Total Travel**				11,765.17
1. Domestic Travel Costs (including Canada, Mexico, and U.S. possessions)				11,765.17
2. Foreign Travel Costs				0.00
E. Trainee/Participant Costs (Total Participants: 0) **Total Trainee/Participants**				0.00
1. Tuition/Fees/Health Insurance				0.00
2. Stipends				0.00
3. Trainee Travel				0.00
4. Subsistence				0.00
5. Other				0.00
F. Other Direct Costs **Total Other Direct Costs**				13,366.83
1. Materials and Supplies				0.00
2. Publication Costs/Documentation/Dissemination				3,852.14
3. Consultant Services				0.00
4. Computer (ADP) Services				0.00
5. SubAwards/Consortium/Contractual Costs				0.00
6. Equipment or Facility Rental/User Fees				0.00
7. Alterations and Renovations				0.00
8. Intern & Fellow M&A ($5,069.94) and Material Service Charge ($4,444.75)				9,514.69
9.				0.00
10.				0.00
G. Direct Costs **Total Direct Costs (A through F)**				339,802.42
H. Indirect Costs **Total Indirect Costs**				160,197.58
Organizational Overhead:				60,603.59
G&A:				45,239.52
LDRD & Service Assessment:				31,820.32
PDM:				22,534.15
I. Direct and Indirect Costs **Total Direct and Indirect Costs (G+H)**				500,000.00

Budget Period: 2 Duration: 12 months	DOE Funded Person-mos. CAL	ACAD	SUMR	Funds Requested ($) (Salary+Fringe)
A. Senior Personnel: PI/PO, Co-PI's, Faculty and Other Senior Associates — **Total Senior Personnel (1-8)**				90,564.20
1. Fan, Jiwen	6	0	0	90,564.20
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9. Others (See Attachment for Details)				0.00
B. Other Personnel (Number in Brackets) — **Total Other Personnel**				166,480.28
(2) Post Doctoral Associates	24			164,658.74
(0) Graduate Students				0.00
(0) Undergraduate Students				0.00
(1) Secretarial / Clerical	0.1			451.43
(1) Project Coordinator	0.2			1,370.11
Total Personnel Costs — **Total Salaries and Wages (A+B)**				257,044.48
C. Permanent Equipment — **Total Permanent Equipment**				0.00
D. Travel — **Total Travel**				65,141.85
1. Domestic Travel Costs (including Canada, Mexico, and U.S. possessions)				57,646.66
2. Foreign Travel Costs				7,495.19
E. Trainee/Participant Costs (Total Participants: 0) — **Total Trainee/Participants**				0.00
1. Tuition/Fees/Health Insurance				0.00
2. Stipends				0.00
3. Trainee Travel				0.00
4. Subsistence				0.00
5. Other				0.00
F. Other Direct Costs — **Total Other Direct Costs**				12,885.62
1. Materials and Supplies				0.00
2. Publication Costs/Documentation/Dissemination				5,906.70
3. Consultant Services				0.00
4. Computer (ADP) Services				0.00
5. SubAwards/Consortium/Contractual Costs				0.00
6. Equipment or Facility Rental/User Fees				0.00
7. Alterations and Renovations				0.00
8. Intern & Fellow M&A ($6,689.49) and Material Service Charge ($289.43)				6,978.92
9.				0.00
10.				0.00
G. Direct Costs — **Total Direct Costs (A through F)**				335,071.95
H. Indirect Costs — **Total Indirect Costs**				164,928.05
LDRD & Service Assessment:				31,820.30
PDM:				22,319.85
Organizational Overhead:				63,193.56
G&A:				47,594.34
I. Direct and Indirect Costs — **Total Direct and Indirect Costs (G+H)**				500,000.00

Budget Period: 3 Duration: 12 months	DOE Funded Person-mos. CAL	ACAD	SUMR	Funds Requested ($) (Salary+Fringe)
A. Senior Personnel: PI/PO, Co-PI's, Faculty and Other Senior Associates — **Total Senior Personnel (1-8)**				92,684.94
1. Fan, Jiwen	6	0	0	92,684.94
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9. Others (See Attachment for Details)				0.00
B. Other Personnel (Number in Brackets) — **Total Other Personnel**				171,766.96
(2) Post Doctoral Associates	24			169,887.68
(0) Graduate Students				0.00
(0) Undergraduate Students				0.00
(1) Secretarial / Clerical	0.1			465.74
(1) Project Coordinator	0.2			1,413.54
Total Personnel Costs — **Total Salaries and Wages (A+B)**				264,451.90
C. Permanent Equipment — **Total Permanent Equipment**				0.00
D. Travel — **Total Travel**				49,206.31
1. Domestic Travel Costs (including Canada, Mexico, and U.S. possessions)				41,662.05
2. Foreign Travel Costs				7,544.26
E. Trainee/Participant Costs (Total Participants: 0) — **Total Trainee/Participants**				0.00
1. Tuition/Fees/Health Insurance				0.00
2. Stipends				0.00
3. Trainee Travel				0.00
4. Subsistence				0.00
5. Other				0.00
F. Other Direct Costs — **Total Other Direct Costs**				15,922.54
1. Materials and Supplies				0.00
2. Publication Costs/Documentation/Dissemination				9,456.18
3. Consultant Services				0.00
4. Computer (ADP) Services				0.00
5. SubAwards/Consortium/Contractual Costs				0.00
6. Equipment or Facility Rental/User Fees				0.00
7. Alterations and Renovations				0.00
8. Intern & Fellow M&A ($6,003.01) and Material Service Charge ($463.35)				6,466.36
9.				0.00
10.				0.00
G. Direct Costs — **Total Direct Costs (A through F)**				329,580.75
H. Indirect Costs — **Total Indirect Costs**				170,419.25
G&A:				51,462.49
LDRD & Service Assessment:				31,820.32
Organizational Overhead:				64,988.20
PDM:				22,148.24
I. Direct and Indirect Costs — **Total Direct and Indirect Costs (G+H)**				500,000.00

Budget Period: 4 Duration: 12 months	DOE Funded Person-mos. CAL	ACAD	SUMR	Funds Requested ($) (Salary+Fringe)
A. Senior Personnel: PI/PO, Co-PI's, Faculty and Other Senior Associates — **Total Senior Personnel (1-8)**				96,271.18
1. Fan, Jiwen	6	0	0	96,271.18
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9. Others (See Attachment for Details)				0.00
B. Other Personnel (Number in Brackets) — **Total Other Personnel**				178,394.34
(2) Post Doctoral Associates	24			176,442.24
(0) Graduate Students				0.00
(0) Undergraduate Students				0.00
(1) Secretarial / Clerical	0.1			483.79
(1) Project Coordinator	0.2			1,468.31
Total Personnel Costs — **Total Salaries and Wages (A+B)**				274,665.52
C. Permanent Equipment — **Total Permanent Equipment**				15,240.38
PNNL Institutional Computing: 15,240.38;				
D. Travel — **Total Travel**				21,983.96
1. Domestic Travel Costs (including Canada, Mexico, and U.S. possessions)				14,140.36
2. Foreign Travel Costs				7,843.60
E. Trainee/Participant Costs (Total Participants: 0) — **Total Trainee/Participants**				0.00
1. Tuition/Fees/Health Insurance				0.00
2. Stipends				0.00
3. Trainee Travel				0.00
4. Subsistence				0.00
5. Other				0.00
F. Other Direct Costs — **Total Other Direct Costs**				16,016.37
1. Materials and Supplies				0.00
2. Publication Costs/Documentation/Dissemination				8,989.64
3. Consultant Services				0.00
4. Computer (ADP) Services				0.00
5. SubAwards/Consortium/Contractual Costs				0.00
6. Equipment or Facility Rental/User Fees				0.00
7. Alterations and Renovations				0.00
8. Intern & Fellow M&A ($5,610.86) and Material Service Charge ($1,415.87)				7,026.73
9.				0.00
10.				0.00
G. Direct Costs — **Total Direct Costs (A through F)**				327,906.23
H. Indirect Costs — **Total Indirect Costs**				172,093.77
Organizational Overhead:				67,245.40
PDM:				22,203.85
G&A:				50,824.23
LDRD & Service Assessment:				31,820.29
I. Direct and Indirect Costs — **Total Direct and Indirect Costs (G+H)**				500,000.00

Budget Period: 5 Duration: 12 months	DOE Funded Person-mos.			Funds Requested ($) (Salary+Fringe)
	CAL	ACAD	SUMR	
A. Senior Personnel: PI/PO, Co-PI's, Faculty and Other Senior Associates **Total Senior Personnel (1-8)**				101,166.01
1. Fan, Jiwen	6.1	0	0	101,166.01
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9. Others (See Attachment for Details)				0.00
B. Other Personnel (Number in Brackets) **Total Other Personnel**				184,903.00
(2) Post Doctoral Associates	24			182,879.84
(0) Graduate Students				0.00
(0) Undergraduate Students				0.00
(1) Secretarial / Clerical	0.1			501.39
(1) Project Coordinator	0.2			1,521.77
Total Personnel Costs **Total Salaries and Wages (A+B)**				286,069.01
C. Permanent Equipment **Total Permanent Equipment**				0.00
D. Travel **Total Travel**				21,907.07
1. Domestic Travel Costs (including Canada, Mexico, and U.S. possessions)				21,907.07
2. Foreign Travel Costs				0.00
E. Trainee/Participant Costs (Total Participants: 0) **Total Trainee/Participants**				0.00
1. Tuition/Fees/Health Insurance				0.00
2. Stipends				0.00
3. Trainee Travel				0.00
4. Subsistence				0.00
5. Other				0.00
F. Other Direct Costs **Total Other Direct Costs**				15,578.97
1. Materials and Supplies				0.00
2. Publication Costs/Documentation/Dissemination				9,307.33
3. Consultant Services				0.00
4. Computer (ADP) Services				0.00
5. SubAwards/Consortium/Contractual Costs				0.00
6. Equipment or Facility Rental/User Fees				0.00
7. Alterations and Renovations				0.00
8. Intern & Fellow M&A ($5,815.58) and Material Service Charge ($456.06)				6,271.64
9.				0.00
10.				0.00
G. Direct Costs **Total Direct Costs (A through F)**				323,555.05
H. Indirect Costs **Total Indirect Costs**				176,444.95
G&A:				52,406.59
Organizational Overhead:				70,110.60
PDM:				22,107.45
LDRD & Service Assessment:				31,820.31
I. Direct and Indirect Costs **Total Direct and Indirect Costs (G+H)**				500,000.00

Cumulative Total	Subtotal	Totals ($)
Section A, Senior/Key Person		467,661.42
Section B, Other Personnel		862,739.91
Total Number Other Personnel	20	
Total Salary, Wages and Fringe Benefits (A+B)		1,330,401.33
Section C, Equipment		81,740.38
Section D, Travel		170,004.36
1. Domestic	147,121.31	
2. Foreign	22,883.05	
Section E, Participant/Trainee Support Costs		0.00
1. Tuition/Fees/Health Insurance	0.00	
2. Stipends	0.00	
3. Travel	0.00	
4. Subsistence	0.00	
5. Other	0.00	
Number of Participants/Trainees	0	
Section F, Other Direct Costs		73,770.33
1. Material and Supplies	0.00	
2. Publication Costs	37,511.99	
3. Consultant Services	0.00	
4. ADP/Computer Services	0.00	
5. Subawards/Consortium/Contractual Costs	0.00	
6. Equipment or Facility Rental/User Fees	0.00	
7. Alterations and Renovations	0.00	
8. Other 1	36,258.34	
9. Other 2	0.00	
10. Other 3	0.00	
Section G, Direct Costs (A thru F)		1,655,916.40
Section H, Indirect Costs		844,083.60
Section I, Total Cost of Project (G+H)		2,500,000.00

Proposal Tracking Number: 228270

BUDGET JUSTIFICATION

Battelle Memorial Institute is the contractor that operates PNNL for the U.S. Department of Energy (DOE). PNNL does not receive core funding for our operations by DOE. PNNL must be successful in proposing and attracting all funding and grants to maintain our research and laboratory operations and staff.

In compliance with the requirements of Program Announcement LAB 16-1625, the budget for this project is the minimum award size of $2.5M over 5 years, and the Principal Investigator's level of effort is within the range of a minimum of 50% and a maximum of 100%. As stated in the Program Announcement "The size of a national laboratory award is commensurate with the requirement to charge 12-month annual salaries (compared with professors, who are partially paid by academic institutions)."

A. Senior Personnel

Dr. Jiwen Fan, PI, 30.2 person-months, which meets the requirement of a minimum of 50% for the PI's effort. Fan will be responsible for achieving the objectives of the project and reporting progress to program managers. She will oversee all the tasks to ensure objectives are achieved on time. She will instruct two postdocs each year as well as conduct the work related to the WRF-SBM-MOSAIC model simulations and the aerosol impacts related to wildfires and urbanization.

B. Other Personnel

The labor cost for a Level II postdoctoral associate is estimated to be approximately $105K per year for project Year 1 (July 15, 2017 to July 14, 2018). This low annual rate to the project is achieved through a laboratory decision to apply a reduced overhead rate as applicable to the postdoctoral associate job family.

Postdoctoral Associate, 60.0 person-months, will mainly work on the process-level studies of STs influenced by wildfires and urbanization, focusing on the impacts of changes in land surface properties. The postdoc will also conduct observational analysis for cases studies, and help with global data analysis at the later period of the project.

Postdoctoral Associate, 60.0 person-months, will mainly work on the long-term observational data analysis (at the early period of the project), and the NH-ACME regional refinement (RR) configuration, simulations, and analysis. The postdoc will be visiting Sandia National Laboratory (SNL) in the second year to learn about NH-ACME and the regional refinement (RR) configuration from Drs. Taylor and Roesler.

Project Coordinator, 0.8 person-months, will provide financial support to help build and manage budgets, manage any procurements, and other project related tasks.

Administrator, 0.4 person-months, will provide administrative support to coordinate travel, process publications, and other project related tasks.

C. Equipment Description

PNNL Institutional Computing (PIC) is a laboratory-level investment in research computing to augment multidisciplinary collaborative scientific research. Base capabilities are supplemented by compute nodes and storage bricks acquired by individual PNNL projects using programmatic funds. Three petabytes of data storage/archive is available on tapes. While access to this cluster is free, throughput is greatly enhanced by purchasing nodes. To secure computing resources for the WRF and WRF-Chem model simulations, we propose to purchase 14 compute nodes on Constance, a supercomputer supported through the PIC for project use across the laboratory. Funds are requested for to acquire 14 nodes ~$66,500 in Year 1, which will provide 11.2 M core-hours in total for at most a four-year period. To secure computing resources for observational analysis and modeling data analysis in Year

Received Date: 11/14/2016

4 and Year 5, we request funds in the amount of $14,250 in year 4 for another 3 nodes, which will provide an additional 2.4 M. core-hours for Year 4 and Year 5. Total funds requested is $81,740.38.

D. Travel

Travel estimates, including transportation and subsistence, were derived from Travel Management Partners and U.S. General Services Administration travel policies and regulations. Travel Management Partners is a large travel agency contracted by PNNL.

Conference travel by staff and postdoctoral associates on this project is essential to disseminate results, build collaborations, and keep abreast of advancements in the field.

Funds are requested for the following travel:

- The PI to attend the DOE PI meeting annually in Washington, D.C. $15,233.61 over 5 years
- The PI to attend every other year the AMS Conference on Severe Local Storms. The location of the conference changes each year. We used the destination of New Orleans, LA for calculating the budget. $8,810.44 over 5 years
- The PI and a postdoctoral associate to attend the ARM/ASR meeting in Washington, DC to gain better understanding of ARM measurements or the ACME project meetings to understand the recent developments about the ACME model each year. $23,576.75 over 5 years
- The PI in Year 1 and the PI and postdoctoral associates in Years 2-5 to attend the AGU fall conference in San Francisco, CA, to present project results. $34,912.27 over 5 years
- The PI (or a postdoctoral associate) to attend European Geophysics Union (EGU) conferences two times during the five year period to present findings at international conferences and enhance interactions with people who study severe weather in Europe. The meeting location changes each year. We use the destination of London, UK for calculating the budget. $15,338.79 over Years 2 and Year 4.
- The PI (or a postdoctoral associate) to attend the Asia Oceania Geosciences Society (AOGS) annual meeting in Year 3, to present findings and enhance interactions with people who study severe weather in Asia. The annual meeting of AOGS usually have good sessions for severe storm studies and the PI has been collaborating with Chinese scientists to investigate aerosol impacts on severe thunderstorms in China for many years. The meeting location changes each year. We use the destination of Beijing, China for calculating the budget. $7,544.26 during Year 3.
- A postdoctoral associate to visit Sandia National Laboratories in the later Year 2 for 5 days to work with Drs. Mark Taylor and Erika Roesler in learning about the ACME model with the non-hydrostatic (NH) dynamical core and starting the work on configuration regionally-refined framework for this project. $2,712.90 during Year 2.

E. Trainee/Participant Costs

Not applicable.

F. Other Direct Costs

1. Materials and Supplies: Not applicable.
2. Publication Costs/Documentation/Dissemination: Funds in the amount of $37,511.99 are requested for costs associated with disseminating project results to the scientific community in peer-reviewed journals.

3. Consultant Services: Not applicable.
4. Computer (ADP) Services: Not applicable.
5. SubAwards/Consortium/Contractual Costs: Not applicable.
6. Equipment or Facility Rental/User Fees: Not applicable.
7. Alterations and Renovations: Not applicable.
8. Other:
   - Procurement/subcontract service charge is for the placing and administering of procurements and subcontracts, $7,069.46.
   - Intern and fellow management and administration service center charge for the development and implementation of the science education programs, $29,188.88.
   - Alternate Sponsored Fellows (ASF) is a program to reimburse visiting students/scientists for travel and living allowances (housing and/or meals) while conducting research at PNNL. ASFs are not considered employees of PNNL, Battelle, or DOE during their Alternate Sponsored Fellowship visit. The ASF program offers a mechanism for PNNL staff to collaborate with colleges/universities, government agencies or institutes and is available to bring in students, postdocs, faculty and visiting scientists who may contribute to project deliverables. One visiting scientist is budgeted for living allowances in Year 2 to conduct research with us on the severe storm dynamics. $42,989.41 for 12 months. And one visiting student is budgeted for living allowances in Year 3 to conduct research with us on the evaluation of the performance of the fire model. $18,885.93 for 12 months.

G. Direct Costs: $1,655,916

H. Indirect Costs: $844,084

Organizational Overhead: Organizational overhead represents costs for management, supervision, and administration of technical departments and is based on total labor hours, not a percentage rate. Organizational Overhead for each respective research organization also includes costs for buildings and utilities, small tools, lab supplies, laundry, maintenance, and expenses associated with equipment (unless the equipment is assigned to a specific equipment center).

Organizational Overhead for Intern Fellows will be used to collect and recover Intern-associated costs, such as office space, computer workstations, mandatory training requirements, and other similar expenses. This overhead will apply only to exempt students, primarily postdoctoral and some post-baccalaureate, post-masters job families. Non-exempt students, primarily pre-baccalaureate/graduate students, and some post-baccalaureate and post-masters job families are short term, usually are not assigned office space, and typically do not receive a new computer or amenities an exempt staff member would require.

Program Development and Management (PDM): The PDM pool is used to accumulate the costs associated with business development and program integration activities.

General and Administrative Expense (G&A): G&A includes functions such as Accounting, Legal, and Personnel department costs.

Service Assessment: Service Assessment includes the fee DOE pays its Management and Operations (M&O) contractor, and costs paid to DOE for plant-wide support services, such as fire, library, mail, and road maintenance.

Laboratory Directed Research and Development (LDRD): LDRD is research and development work of a creative and innovative nature for the purpose of maintaining the scientific and technological vitality of the Laboratory and/or responding to new scientific or technological opportunities.

I. Direct and Indirect Costs: $2,500,000

U.S. DEPARTMENT OF ENERGY | Office of Science

Understanding Severe Thunderstorms in the Central United States

Pacific Northwest National Laboratory
Street address: 902 Battelle Blvd., Richland WA 99354
Postal Address: P.O. Box 999, Richland, WA 99352

Principal Investigator (PI): Jiwen Fan
Position Title of PI: Scientist
(509) 375-2116 | jiwen.fan@pnnl.gov

DOE National Laboratory Announcement Number: LAB 16-1625

DOE/Office of Science Program Office: Biological and Environmental Research

Topic Area: * See next page for additional information.

Topic Area Program Manager: Renu Joseph

Year Doctorate Awarded: 2007

Number of Times Previously Applied: 0

PAMS Preproposal Number: PRE-0000009698

PECASE Eligible: Yes

Proposal Contains Biographical Sketch in Appendix 1: Yes

Proposal Contains Data Management Plan in Appendix 6: Yes

Pacific Northwest NATIONAL LABORATORY

Proudly Operated by **Battelle** *Since 1965*

PROJECT NARRATIVE

1 Introduction

Severe thunderstorms (STs) comprise an extreme class of deep convective clouds that produce large hail, damaging winds and/or tornadoes, and torrential rainfall. STs frequently cause as much annual property damage and more deaths than hurricanes in the U.S. based on NOAA Storm Prediction Center (NSPC) (2012). Such STs are generally known as supercell storms. Thunderstorms can evolve into supercell storms that are well-organized, monolithic units of vigorous long-lasting convection in the environment with high convective available potential energy (CAPE) and large wind shear. There is considerable evidence that occurrence and intensity of climate extremes such as floods and droughts have been increasing in recent decades, and continued global warming will likely amplify these changes (IPCC 2012). However, projecting the changes of STs has remained a prominent uncertainty in assessing the impacts of climate change (Kunkel et al. 2013; Melillo et al. 2014).

Despite the increasing concern about changes of STs that cause substantial damage, there has been limited research in the relationship of STs with the global climate. This is partly because inconsistent observational reporting may be obscuring storm trends that accompanied the twentieth-century anthropogenic global warming (Brooks 2013; Brooks and Dotzek 2008; Diffenbaugh et al. 2008). Furthermore, the small horizontal scale of the phenomena challenges attribution and projection of ST by global models with typical resolutions of 100-km or larger. Therefore, research has focused on identifying environmental variables favorable for severe convective storms such as convective available potential energy (CAPE) and vertical wind shear, and evaluating how these variables will respond to increasing atmospheric greenhouse gas (GHG) concentrations. However, two significant problems exist with that approach: (1) those variables only account for the control of large-scale environments while ignoring impacts of other physical factors such as land-surface and aerosols, which could change the nature of STs through small-scale physical processes and feedbacks (Brooks 2013); and, (2) there is an implicit but unjustified assumption that the mechanisms responsible for ST initiation will not experience significant future changes (Trapp et al. 2007, Seeley and Romps 2015).

To address the above-mentioned problems, two challenges must be surmounted. First, although there is good understanding about supercell and tornado dynamics (Davies-Jones 2015), we need to improve our fundamental understanding of impacts of other environmental factors such as land-surface and aerosols on ST occurrence and intensity. The ST initiation and intensification are operated by a complex system involving the interactions among dynamics, microphysics and aerosols, and land-surface processes. For example, the feedback of latent heating and cooling from cloud microphysics can affect storm intensity and occurrence of secondary storms. Aerosols may further complicate this through aerosol-cloud interactions. Land-surface characteristics impact surface temperature (T), soil moisture, etc., and then change convective initiation and intensity. However, few studies have focused on the interactions among all these processes and their impacts in STs, which are the foci of this proposal.

The second challenge is to resolve the storm-scale physical processes and feedbacks that impact the nature of STs in global climate models (GCMs). This has been computationally prohibitive for long-term global climate simulations. With advances in computing power and GCM modeling frameworks, it is now feasible to run GCMs using a variable resolution configuration with a much higher resolution over a region of interest (Sakaguchi et al. 2015; Zhao et al. 2016). The Accelerated Climate Modeling for Energy (ACME) model is a newly developed GCM by the Department of Energy (DOE) and the current development in physics is aimed at high-resolutions up to ~ 10 km. However, it will be still too coarse to resolve processes associated with STs. Fortunately, a non-hydrostatic (NH) dynamical core is being developed in the ACME regional refinement (RR) framework by Dr. Mark Taylor at Sandia National Laboratory (SNL). The NH dynamical core makes it possible to perform simulations with ACME at a few km resolutions over a focused region to explicitly resolve STs. A preliminary version of the NH-ACME will be available on an ACME branch in January 2017. This proposed research seizes the opportunity to use the new advances in the ACME model framework to address the above-mentioned two problems and study the past and future ST characteristics.

The continental United States (CONUS) is a global hotspot of ST occurrence, and the central United States (CUS) is a well-known regional hotspot known as "Tornado Alley". The CUS experiences frequent STs in spring and summer (e.g., Trapp et al. 2007). Climate models project an increase in CAPE in the United States (U.S.) from warming, but vertical wind shear is projected to decrease (e.g., Trapp et al. 2007); the net effect is a more favorable environment supporting STs in the 21st century. Besides changes in large-scale CAPE and wind shear in response to increasing GHG emissions, other environmental factors that might influence occurrence and severity of STs through physical-dynamic interactions at small scales are evolving as well. For example, urbanization may impact storm initiation and intensity through modifying land-surface conditions and increasing aerosols (Haberlie et al. 2015), and CUS is projected to urbanize further in the next decades. Wildfires, which may impact STs through long-range transported aerosols (Wang et al. 2009, Saide et al. 2015), have been occurring more frequently in response to climate warming, and are projected to increase in frequency more significantly in the future (United States Department of Agriculture (USDA), 2014), especially in Western United States. Concurrent projected increases in the frequency of extreme precipitation, floods, and droughts from climate warming can cause extreme soil moisture conditions, which feed back to the atmosphere and might affect ST development. In addition, recent studies found a temporal change of spatial patterns in tornado activity, i.e., eastward shift from Texas/Oklahoma, the traditional ‘‘Tornado Alley’’ during 1954-1983 (cold period), to Tennessee/Alabama during 1984-2013 (warm period) (Agee et al. 2016).

Therefore, predicting changes of STs in a warmer climate requires understanding and modeling of the fundamental processes governing their development and evolution, and how these processes interact with the changing climate and environments. In this proposed project, I will take advantage of the most recent progress in process-level modeling and observations, and new advances of the ACME model framework with the NH dynamical core, to address the above-mentioned significant challenges, and answer the following overarching science questions:

Q1. What are the significant interactions of storm dynamics with the environmental factors of land-surface, aerosols, and extreme precipitation impacting ST occurrence and intensity? How do urbanization and wildfires affect ST characteristics (i.e., occurrence, intensity, and spatial distribution) over the CUS?

Q2. How may future human activities, i.e., climate warming and urbanization, perturb the interactions of storm dynamics with the environmental factors of land-surface, aerosols, and precipitation to influence ST characteristics in the CUS?

Q3. What are the overall effects of the compounding extremes (i.e., climate warming, increased wildfires, more extreme precipitation, and urbanization) on ST characteristics over the CUS in future? What are the respective impacts of future urbanization and climate warming on ST characteristics?

1.1 Background and evaluation of existing knowledge

1.1.1 Past understanding of STs

The dynamics of supercells and tornadoes is understood quite well (Davies-Jones 2015 and papers therein). Significant characteristics of supercells and other STs are the rotating updraft cores, which can be characterized by high updraft helicity (UH). In addition, radar reflectivity (Ze) in updraft cores is large (>50 dBZ based on NCDC 2009). The criteria combining UH with Ze can be used to identify STs. The ST-favorable environments are high CAPE and deep vertical wind shear. Our recent study showed that increasing wind shear at 5-10 km altitude fosters the formation of mesocyclone and supercell-like convective systems (Chen et al. 2015), consistent with Coniglio et al. (2006).

Over the CUS in spring and summer, supercells form in the warm sector of the mid-latitude trough (low pressure) system and propagate in line with the cold front of the low pressure system. Past understanding of STs primarily focused on cloud dynamics. However, as discussed above, physical processes such as land-surface processes and aerosol-cloud interactions could impact storm dynamics and therefore ST occurrence and intensity. For example, microphysics that is sensitive to aerosols can affect updraft speeds through latent heating and condensate loading. Recent studies began to explore impacts of aerosols, mainly with idealized-case configurations in land surface and/or aerosols. Those studies identified aerosol impacts on supercell intensity, tornado genesis, and hailstone size (e.g., Ilotoviz et al. 2016; Lerach and Cotton 2012; Loftus and Cotton 2014) as well as the influence of urbanization on storm initiation, intensity, and spatial distribution (e.g., Haberlie et al. 2015, Niyogi et al. 2011, Shepherd et al. 2002). However, in an interactive environment with all these factors operating, it is unknown how significant each effect could be. Studies showed that a small perturbation of lower-level moisture, temperature, and wind shear by other processes could easily mask the aerosol effects (Lerach and Cotton 2012; Loftus and Cotton 2014). A larger anvil area induced by aerosol-cloud interactions (ACI) could buffer aerosol invigoration of convection through the enhanced surface cooling over a regional domain and a timescale of weeks (Fan et al. 2013). Therefore, comprehensive examination with a large number of cases as proposed in this research is key to improving our understanding of the significant factors affecting STs in the CUS.

Studies showed a general sensitivity of simulated supercells to microphysics parameterization (e.g., Morrison et al. 2015; Dawson et al. 2016). The one-moment or two-moment schemes used by the current global and regional climate models have many limitations in representing cloud microphysical processes such as droplet diffusional growth, conversion of droplets to raindrops, and excessive size sorting (as summarized in Khain et al. 2015 and Fan et al. 2016a), and are not designed for studying ACI. Bin microphysics explicitly calculates evolution of hydrometeors over each size bin, and can provide a more rigorous numerical solution and more physical representations of microphysical processes, although it suffers from many of the same inherent uncertainties as bulk schemes (e.g., assumed particle types, densities, etc). Many studies have shown that bin microphysics schemes, especially the spectral-bin microphysics (SBM; Khain et al. 2004) method, predicted more realistic precipitation than bulk scheme simulations for single deep convective cases, as summarized in Khain et al. (2015) and more realistic updraft velocity compared to multi-Doppler radar retrievals (Fan et al. 2015b). Although computationally expensive, the PI has been using the SBM to conduct case studies and even month-long simulations over a few regions (Fan et al. 2013) to improve process-level understanding.

Precipitation strongly modulate soil moisture, which can influence the development of the daytime planetary boundary layer (PBL) and thereby the initiation and intensity of convection (e.g., Eltahir 1998). Studies have shown that the formation and intensity of secondary circulation triggering convection are highly affected by soil moisture content (Findell and Eltahir 2003) and its horizontal gradient (Taylor et al. 2010). CAPE is also usually higher over areas with enhanced soil moisture, because a higher latent heat flux leads to a moister convective boundary layer and a higher equivalent potential temperature (Pielke 2001). Deep convection forms more often over the regions with more significant soil moisture contrast between wet and dry soils (Taylor et al. 2010). The CUS is a hotspot for strong soil moisture-precipitation feedback (Koster et al. 2004). Coarse-resolution GCMs cannot resolve the processes associated with this feedback and convective parameterization in GCM results in a too strong positive feedback (Taylor 2015). In a future climate, more extreme precipitation would lead to more extreme soil moisture content and possibly a more significant soil moisture contrast as well because of a geranial trend of drying over land as a result of higher evaporative demand with warmer *T* (Dirmeyer et al. 2013), which might enhance storm occurrence and intensity. As proposed in this research, GCM simulations at a convection-permitting scale can explore this link more realistically and particularly advance the understanding of the soil moisture-precipitation feedback on ST characteristics.

1.1.2 Possible impacts of wildfires

Wildfires could impact convection through three major pathways as outlined by black arrows in Fig. 1. The first pathway is through aerosol impacts. Wildfires are a globally important source of aerosol particles and produce a large amount of primary organic aerosols and secondary organic aerosols (SOA). Black carbon is the major composition of smoke aerosols, which can significantly change the heating profile of the atmosphere and radiation balance on the surface through aerosol-radiation interactions (ARI). These effects could change local circulation and dramatically affect storm intensity (Fan et al. 2008) and escalate a convective event to a severe storm event (Fan et al. 2015a) Aerosol particles such as wildfire-produced SOA could modify cloud microphysics, then convection intensity and precipitation by acting as cloud condensation nuclei (CCN) or ice nuclei (IN) (e.g., Andreae et al. 2004; Rosenfeld et al. 2008; Khain et al. 2005, Fan et al. 2007b, 2012b). Smoke aerosols transported from Central American fires were linked to severe weather over the CUS through ACI (e.g., Wang et al. 2009; Fig. 2). A more recent study suggested adding smoke aerosols transported from Central America to an environment already conducive to ST development can increase the likelihood of significant tornado occurrence in the CUS through both ACI and ARI (Saide et al. 2015). These ideas are mainly conceptual

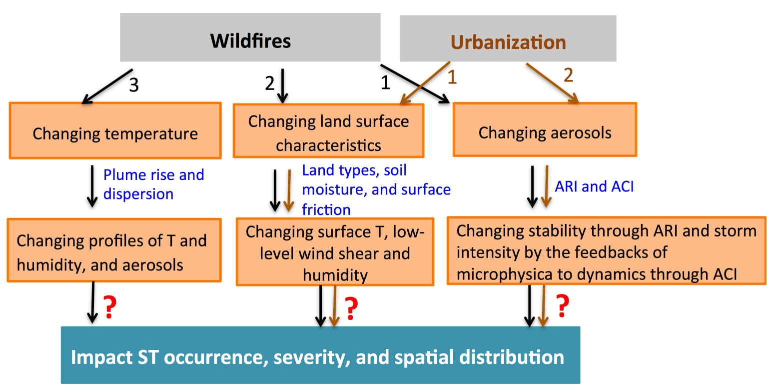

Fig. 1 Pathways for wildfires and urbanization to impact ST characteristics. Black arrows denote the pathways for wildfires and brown arrows for urbanization. The question marks denote the understanding to be gained from this proposed work.

and further studies with the most advanced cloud-microphysics models are needed to construct convincing mechanisms.

The second pathway is through changes in land-surface properties such as surface roughness, albedo, and soil moisture, which would impact surface friction, temperature, and latent and sensible heat that change the PBL structure, lower-level moisture, and wind shear (Fig. 1). However, no studies have specifically investigated the impacts of this pathway on STs.

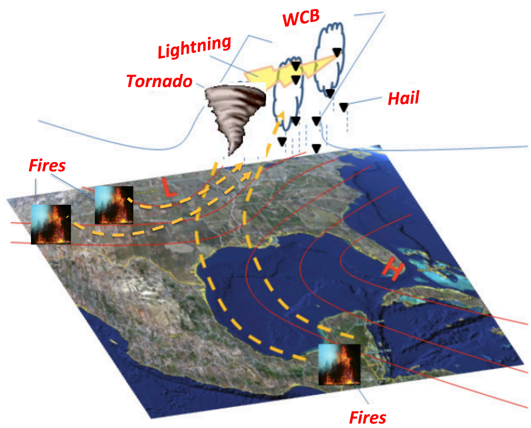

Fig. 2 A conceptual diagram for the possible impacts on STs from wildfires in Central America and over the Rocky Mountains and the region further west. The red lines denote that background mean flows of the subtropical Bermuda high (H) and the mid-latitude trough (L). The blue lines confine a warm conveyor belt (WCB) generally associated with a cold front system and cyclogenesis. The dashed orange lines denote transport of air masses. Modified from Wang et al. (2009).

The third pathway is through changing *T* because wildfire flames heat the environment dramatically and could significantly perturb the synoptic environment if the burned area is large (Fig. 1). Flame tip temperatures for wildfires are about 320~400°C, and can be about 1100-1200 °C for large pools of fires at the continuous flame region (Sullivan et al. 2003). The heat plumes may also transport heat and aerosol particles from the lower-troposphere to elevated levels, impacting convection environments. Thus, modeling of fire emissions and plume dispersion is very important to the vertical transport of heat, moisture, and chemicals/aerosols (Betts et al. 2010), but is poorly represented in current regional and GCMs because of coarse model resolutions. A plume dispersion model was considered in a coarse-resolution Brazilian regional model to simulate plume dispersion (Freitas et al. 2007; 2009). In this proposed project I will consider plume dispersion to more comprehensively investigate the impact of wildfires in the ACME model.

STs over the CUS could be affected by wildfires in Central America and the Rocky Mountains and mountains further west (Fig. 2). Central American wildfires can affect STs through transported smoke aerosols as suggested by Wang et al. (2009) and Saide et al. (2015), and the possible perturbation to the subtropical Bermuda high pressure system transporting moisture and aerosols to the CUS through the second and third pathways that have never been considered. As for the impacts of wildfires over the Rocky Mountains, because a significant number of storms over the CUS originate from that location, all three major pathways listed in Fig. 1 might have a significant effect. For wildfires over the coastal mountain ranges (i.e., Sierra Nevada and Cascade Mountains), the background northwesterly mean flow could link the remote wildfires over those places with STs in the CUS (Fig. 2) through long-range transported aerosols and a perturbation of a cold front associated with a mid-latitude trough by large heat and land-surface changes. No literature study investigated the impact of wildfires over the western United States (including the Rocky Mountains) on STs in the CUS before. In addition, the above-mentioned potential changes by wildfires to the cold front and subtropical high-pressure system could lead to a spatial shift of ST occurrence. As wildfires are projected to increase in a future warmer climate, it is important to understand how they may have remote and local influence on STs in the CUS through various mechanisms.

1.1.3 Possible impacts of urbanization

Urbanization is an extreme case of land-use change, and it has significant local impacts on weather and climate based on National Climate Assessment (NCA) (2014), including a strong climatological influence on regional thunderstorms (Kellner and Niyogi 2014). Urbanization could impact storm properties through two major pathways as outlined in Fig. 1 (brown arrows). The first pathway is through land-cover changes associated with urbanization that increase surface *T* compared to the surrounding rural area, known as the urban heat island (UHI) effect. Convective storms may be initiated at the UHI convergence zone, created through a combination of increased temperature and mechanical turbulence resulting from complex urban surface geometry and roughness (Bornstein and Lin, 2000; Shepherd, 2005, Hubbart et al. 2014). Urban landscapes can impact sensible and latent heat flux, soil moisture, etc, affecting thunderstorm initiation (Haberlie et al. 2015) and changing the location and amount of precipitation compared to pre-urbanization (Shepherd et al. 2002; Niyogi et al. 2011). Recent observational studies suggested that tornadoes are more frequent and severe in large metro areas compared to nearby, smaller cities (Cusack 2014), and more frequent tornadoes touch down over urban land than forest (Kellner and Niyogi 2014). A few possible mechanisms were hypothesized for such impacts including the UHI enhancing storm severity downwind of the main urban areas and increased surface roughness increasing low-level shear that has been found to favor tornado genesis (Craven et al. 2002). However, the explicit mechanisms have not yet been scrutinized.

The second pathway for the urbanization impacts is through pollutant aerosols associated with industrial and population growth (Fig. 1). Previous studies have shown that urban aerosols invigorate precipitation in urban downwind regions through ACI (Van den Heever and Cotton 2007; Carrió et al. 2010). Few studies have examined the combined effects of both pathways and their relative importance. A very recent study attempting to do this evaluation for a single storm case showed that land-cover changes increased precipitation over the upstream region but decreased precipitation over the downstream region, while aerosols had the opposite effect (Zhong et al. 2015). The study emphasized the large uncertainty in simulated ACI due to limitations of the two-moment bulk microphysical scheme employed. Furthermore, this study did not focus on the ST dynamics and physics.

There are some large and medium cities in the CUS such as Oklahoma City, Kansas City, Dallas, Jackson, and nearby cities. It may be important to consider the role that those cities play in affecting the ST characteristics over the region, but it has not been studied yet.

1.1.4 Current climate modeling studies of STs

As mentioned in the introduction, coarse-resolution climate models cannot resolve STs so identifying the ST-favorable environments in climate simulations is through the large-scale environmental factors of CAPE and vertical wind shear, with equal weight to both variables (e.g., Trapp 2007; Gensini et al. 2014), or more weight to vertical wind shear (e.g., Brooks et al. 2003; Allen et al. 2011). Regardless of the weight given to the two variables, the main source of uncertainty in identifying ST-favorable environments with CAPE and vertical shear is caused by the two problems discussed in the introduction: (1) missing in the storm-scale physical processes and feedbacks (Brooks 2013), and (2) not accounting for factors related to storm initiation from small-scale outflow boundaries such as cold pools to large-scale inversion (Seeley and Romps 2015). Projection of changes in ST-favorable environments under a warming climate has been made under the implicit assumption that convective initiation remains the same, but this assumption is made out of necessity in such studies due to coarse resolution (Trapp 2007; Seeley and Romps 2015). Based on Seeley and Romps (2015), the large overestimation of ST occurrence in southern Texas with the ST-favorable environment index using radiosonde data (Fig. 3) is likely because the index cannot account for the frequently capped elevated inversion layer, which would strongly inhibit the ST occurrence. Thus, this uncertainty regarding storm initiation has limited our ability to translate trends in a ST-favorable environment into projections for future severe thunderstorms.

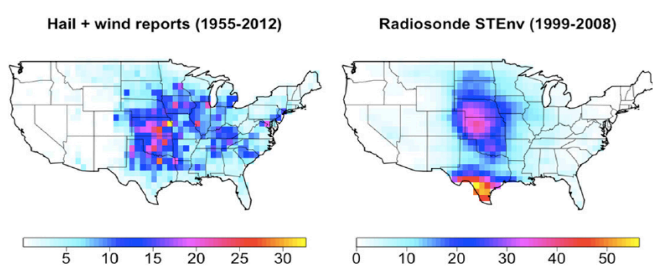

Fig. 3 (left) Mean annual reports of hail greater than 1 in. in diameter or winds in excess of 50 knots from 1955 to 2012. (right) Mean annual ST environment [days per year with (CAPE)(shear) ≥ 36 300 (m $s^{-1})^3$ at 0000 UTC] derived from the radiosonde network for the years 1999–2008. From Seeley and Romps (2015).

Besides storm occurrence and severity, the temporal change of spatial patterns in the U.S. ‘‘tornado climatology’’ is an increasingly important research focus. Agee et al. (2016) found an eastward shift in tornado activity from Texas/Oklahoma, the traditional ‘‘Tornado Alley’’ during 1954-1983, to Tennessee/ Alabama during 1984-2013 that has a warmer *T* than the former (Agee et al. 2016). A regional climate study with a 4-km resolution suggested a similarly eastward shift of STs as a result of the climate warming (Gensini and Mote 2015). However, the underlying reason might be because of the increased wildfires in response to warming. The physical mechanisms for explaining the spatial shift need to be identified.

1.1.5 Impact of climate warming, and future changes of wildfires and urbanization

The global average temperature has increased significantly in the last few decades, mostly as a result of increasing GHG from anthropogenic sources (IPCC 2012). Accompanying the warming are increasing trends in extremes of heat and heavy precipitation events in CONUS (Melillo et al. 2014). For example, extreme precipitation has increased strongly in the Great Plains, Midwest, and Northeast. However, the trends of STs including the intensity and frequency of tornadoes, hail, and damaging thunderstorm winds are uncertain, as discussed in the 2014 NCA; Melillo et al. 2014). Despite various uncertainties in the tornado record, a new study found that the mean annual number of tornadoes has remained relatively constant, but their variability of occurrence has increased since the 1970s (Brooks et al. 2014).

Wildfire is one type of climate extreme. As a result of climate warming, worldwide the wildfire season has become ~ 20% longer over the past 35 years (Jolly et al. 2015). In the United States, climate change has led to fire seasons that are now 78 days longer on average compared to 1970 (USDA 2014). In the western United States, the frequency of large wildfires and the length of the fire season have increased substantially in recent decades (Westerling et al. 2006). Over the next 25 years, the U.S. NCA predicts the nationwide area burned by wildfires will double as global warming leads to higher temperatures, longer wildfire seasons, and more frequent droughts (Melillo et al. 2014). By the end of the century, models project that the burned area in North America could increase by 2 to 5.5 times. The greatest threat and most significant trends will be experienced in the Western United States (Dennison et al. 2014).

Worldwide, urban land and population have grown rapidly over the 20th century. All regions are expected to urbanize further during the coming decades. Africa and Asia are urbanizing faster than other regions. In the United States, urban land is projected to increase from 39.5 million ha in 1997 to 70.5 million ha in 2025 (Agli et al. 2004). Projection suggests significant U.S. urban expansion by 2030, with the magnitude of increase varying by region. By U.S. regions, the urban land areas are projected to increase by 75% in the south, 80% in the northern Midwest, 81% in the southern Midwest, 71% in the Great Plains, 86% in the southwest, 82% in the northwest, and 98% in California. The south is projected to continue to encompass the most urban area.

1.2 Scientific objectives, deliverable, and impact

I propose to conduct a comprehensive study of STs, from process-level understanding of important physical factors impacting STs, to future changes of STs in a changing climate and environment over the CUS. The objectives of this proposed work are to: 1) improve the foundational understanding of key interactive processes between cloud dynamics, microphysics, aerosols, land surface, and precipitation that impact ST occurrence and intensity, especially concerning (a) the impacts of urbanization and wildfires, and (b) feedbacks of extreme precipitation such as flash flooding through soil moisture conditions to the subsequent ST formation and intensity; 2) provide a comprehensive assessment of the performance of the new NH-ACME with a RR configuration at a convection-permitting scale, in terms of reproducing the observed ST characteristics and representing qualitatively the mechanisms for impacts of wildfires and urbanization gained from the process-level understanding; and 3) gain a more robust understanding of (a) how ST characteristics will change in the CUS by considering the compounding extreme events of droughts (causing wildfires), flash flooding (causing extreme soil moisture), and urbanization in the future, and (b) the relative importance of influences of the future climate warming and urbanization.

The grand deliverable of this proposed research is more advanced understanding of ST activities in the past and future by investigating the unexplored links between STs and the evolving environment impacted by human activities—increased GHG emissions and urbanization. The research fills a significant gap in understanding the important physics-dynamics interactions involving microphysics, aerosols, land surface, and precipitation impacting ST occurrence, intensity, and spatial distribution. Therefore, the research would provide increased understanding of ST activities and change current perception about how severe weather will be impacted by human activities. Additionally, the proposed work would provide the first assessment of the performance of NH-ACME with a RR configuration at a convection-permitting scale in simulating STs, which contributes to the knowledge needed by the climate community in guiding development of and using convection-permitting climate models.

1.3 Program mission relevance

The proposed research aims to improve understanding of ST activities in the past and future by modeling (including WRF/WRF-Chem and ACME) and observational (including Atmospheric Radiation Measurement (ARM) Climate Research Facility data at the Southern Great Plains (SGP) site) studies. It responds directly to the LAB 16-1625 funding opportunity calls for research in “Enhancing our understanding of the physical behavior of the large-scale and localized coupled climate system that gives rise to compounding multivariate extremes, and how these extremes would change in a changing climate". The research will scrutinize the impacts of anthropogenic warming and urbanization on STs and use statistical methods such as Kolmogorov–Smirnov (KS) test to quantify the impacts, responding to the call for research in "Development and use of statistical techniques to characterize these multivariate extremes, quantify their uncertainty, and distinguish the influences of anthropogenic drivers and natural variability". The objectives of the research as stated right above address the DOE's Climate and Environmental Sciences Division (CESD) focus of "Enhancing our understanding of the physical behavior of the large-scale and localized coupled climate system" and the DOE's Biological and Environmental Research (BER) mission to "achieve a predictive understanding of complex biological, climatic, and environmental systems".

The work will use both long-term observational datasets, including cloud, radiation, surface measurements, and soundings, and ARM intensive observational period data including multi-Dopplar radars and aircraft measurements from the ARM SGP site. It uses high-resolution regional models to explicitly bridge the gap between observations and GCMs. In doing so, the research leverages and complements existing capabilities under BER.

2 Previous and on-going research of PI relevant to proposed work

I have broad research experience, from atmospheric chemistry and aerosols, to cloud physics and convection dynamics. My research experience in cloud microphysics and dynamics, aerosol impacts on thunderstorms, land-atmosphere interaction, and impact of urbanization provides a strong foundation for the proposed research. I have been extensively working on process-level modeling of clouds and aerosols using Weather Research and Forecasting (WRF) or the chemistry version of WRF (WRF-Chem)), and on employing observational data from the DOE ARM program to evaluate model simulations and gain understanding. I have also been working on scale-aware convection parameterization, as well as worked on plume dispersion modeling for traffic emissions in my thesis work at the University of Central Florida.

2.1 Aerosol impacts on thunderstorms and impacts of land-use changes and urbanization

I have worked over 10 years on aerosol effects on deep convective clouds (DCCs) with a series of published papers (Fan et al., 2007a, b; 2008, 2009, 2010, 2012a,b, 2013, 2015a, 2016a), and made significant contributions to the understanding of aerosol-DCC interactions by employing and improving the SBM in conjunction with an observational analysis of data from the DOE ARM program. For example, Fan et al. (2009) found that vertical wind shear is one of the key factors determining whether aerosols invigorate or suppress convective intensity. In Li et al. (2011), we examined the long-term impact of aerosols on the vertical development of clouds and rainfall frequencies, using a 10-year dataset of aerosol, cloud and meteorological variables collected from the ARM SGP site. Fan et al. (2012b) suggested that aerosol invigoration of convection as a result of enhanced latent heating might impact circulation. Fan et al. (2013) discovered that a major mechanism leading to the increases of cloud cover, cloud-top height, and cloud thickness with increasing CCN is aerosol microphysical effect (i.e., ACI), through which aerosols induce larger amounts of smaller but longer-lasting ice particles in the stratiform/anvil region of DCCs. This microphysical effect leads to a large surface cooling, which buffers the aerosol invigoration effect.

Besides the contributions to ACI, my work also contributed to the role of ARI in impacting storm intensity and severe weather. Fan et al. (2008) showed that as aerosol light-absorption capability increases, the invigoration of convective intensity and precipitation through the ACI could turn into suppression through the ARI for local storms. Fan et al. (2015a) found black carbon aerosols escalated DCCs to STs causing a catastrophic flood in Southwest China by redistributing the moist static energy between the large Sichuan basin and the mountainous area downwind mainly through ARI. Very recently, my team developed a more advanced modeling system for a process-level study of ACI and ARI by coupling SBM with the sectional aerosol module named Model for Simulating Aerosol Interactions and Chemistry (MOSAIC) in WRF-Chem so that the entire lifecycle processes for both clouds and aerosols can be accounted for in detail (Gao et al. 2016). This advanced model will be used in this proposed study.

In addition, I have experience in coupling a cloud-resolving model with a land surface model (Parameterization for Land-Atmosphere-Cloud Exchange, or PLACE), and modifying surface types and soil properties to more realistically simulate sea-breeze-induced convective clouds in the Houston area (Fan et al. 2008). With more realistic land-cover types, the CRM model more accurately simulated the surface temperature, sensible and latent heat fluxes, and then the thunderstorm in Houston.

Recently, my collaborators and I have examined the impacts of UHI and aerosols due to urbanization on precipitation extremes in the Yangtze River Delta Region of China by conducting 5-year WRF-Chem simulations at 3-km resolution (Zhong et al. 2016). We found that the UHI and the elevated aerosol loading have opposite effects on extreme rainfall frequency in summer, and the impacts strongly depend on different convective systems.

2.2 Storm dynamics and microphysics

I have gained solid knowledge about convective microphysics, dynamics and their interactions from years of studying aerosol-DCC interactions. Besides studies focusing on aerosol impacts, I have been working on convective dynamics and the feedback of microphysics to dynamics for different storm systems. Cheng et al. (2015; a study I mentored) investigated the role of wind shear at different vertical levels in mesoscale convective system (MCS) organization using the WRF model with the SBM. We found that increasing wind shear at altitudes of 0-5 km from a weak wind-shear baseline case leads to a more organized quasi-line convective system, while increasing wind shear at 5-10 km tends to produce a mesocyclone circulation and supercell-like storm. Fan et al. (2015b) used the 3-D wind retrievals from multi-Doppler radars to evaluate the modeled convective updraft intensity by bin- and bulk-microphysics schemes for three different storm systems in the tropics and mid-latitudes, and found that the model with bulk microphysics tends to overestimate convection intensity in the middle and upper troposphere, but the SBM can alleviate much of the overestimation.

To understand model biases in simulating DCCs and major factors that lead to the large model spread at cloud-resolving scales, I have been leading a model intercomparison study of a mesoscale squall-line case over SGP from the Midlatitude Continental Convective Clouds Experiment (MC3E) field campaign using the WRF model at 1-km resolution with eight microphysics schemes (Fan et al., 2016b). The most important observational datasets used are 3-D wind field retrievals from multi-Doppler radars and profiler data. We attributed the large spread of updraft velocity among different microphysics schemes to the joint effects of the low-level perturbation pressure gradient determined by cold pool intensity and buoyancy related to latent heating and condensate loading. In an on-going study, I (with my collaborators) am developing a piggybacking approach following Grabowski (2014, 2015) for the WRF real-case simulations to separate the feedback of microphysics to dynamics.

I am co-leading the PNNL Climate Model Development and Validation (CMDV) project to improve ACME performance in simulating MCSs by further developing the Cloud Layers Unified By Binormals (CLUBB) scheme for deep convection parameterization based on the CLUBB unified scheme for all cloud types including deep convection (Thayer-Calder et al. 2015) and developing cloud microphysics parameterization. Regarding the CLUBB deep development, our CMDV project focuses on reducing the resolution-dependence of simulations including improving Probability density function (PDF) overlap, adding scale dependency of microphysics variances, and developing horizontal advection of CLUBB's higher-order moments. For microphysics, we are developing a three-moment cloud microphysics scheme, which targets alleviation of the two-moment scheme problems in simulating microphysical processes and ACI. Both the CLUBB and microphysics development work is planned for 2018 completion, which can be available for this project's global simulations in early 2019.

3 Proposed work

3.1 Scientific approach

The overall approach consists of three steps outlined in Fig. 4. **First, I will gain a process-level physical understanding through observational analysis and high-resolution WRF or WRF-Chem simulations** (Table 1) with the SBM, MOSAIC, and the Community Land Model (CLM), to answer Q1. Specifically, I will explore (1) how wildfires over the Rocky Mountains and the region further west change storm characteristics in the CUS through the three pathways outlined in Fig. 1, (2) the role of Central America wildfires in changing ST characteristics in the CUS, (3) the contribution of urbanization to ST characteristics through increased anthropogenic aerosols and land use change, and (4) the feedback of soil moisture to ST characteristics focusing on the extreme soil moisture conditions resulting from extreme precipitation/flash floods to the subsequent ST. Observations for single ST cases will be analyzed to evaluate model simulations as I did in previous studies, and to identify significant correlations between ST characteristics and environmental factors for better understanding and to support findings from modeling simulations. These investigations will answer Q1 and achieve Objective #1 to improve the foundational understanding of key interactive physical processes impacting ST characteristics.

We will employ WRF-SBM-MOSAIC (i.e., the bin approach for both aerosol and cloud parameterizations) to provide accurate simulations of both aerosol and cloud lifecycle processes for the benchmark simulation of each case and simulations focusing on ACIs. To save computing cost, for the sensitivity tests on other features such as impact of heat and land-cover changes on large-scale and synoptic systems, we will employ the two-moment bulk scheme from the National Severe Storms Laboratory (NSSL) (Mansell et al. 2010; Mansell and Ziegler 2013). The NSSL scheme explicitly calculates condensation and evaporation, which is different from the majority of bulk schemes, and our previous evaluation showed that the NSSL scheme predicted convective intensity consistent with SBM and the multi-Doppler retrievals (Fan et al. 2016b). I will start with 1-km resolution. For the major mechanisms impacting ST characteristics, I will explore scale-dependencies by testing at 0.3 and 3 km resolutions besides 1-km resolution (i.e., WRF_RES in Table 1). This will show how the major mechanisms impacting ST characteristics change with resolution. The purpose is to better inform the RR grid chosen for NH-ACME simulations in the next step and better understand the potential uncertainties of NH-ACME simulation at a selected resolution. Task 1 in Section 3.2 will provide more specifics.

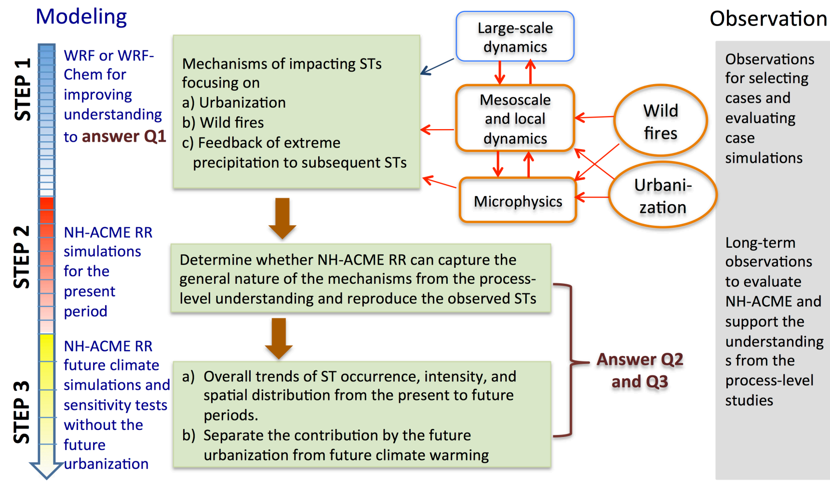

Fig. 4 The schematic figure of the research approach. Red arrows denote the physical processes that this proposal focuses on.

Table 1 Sets of simulations planned (use wildfire as an example for WRF/WRF-Chem simulations)

Simulations	Grid Configuration	Duration	Description
WRF_BASE	Generally 1 km (see details in Section 3.1)	Varying from one to several days	With all three pathways turned on in the case of wild fires
WRF_SENS	Same as WRF_BASE	Same as WRF_BASE	A set of simulations by turning off each pathway or all pathways
WRF_RES	0.3 and 3 km	Same as WRF_BASE	A set of simulations to test the scale-dependencies of the major mechanisms
NH-ACME_P	RR at 1/32° or higher over the CUS	Spring and summer each year for the present period	AMIP-type with observed sea surface temperatures (SSTs) and sea ice distribution (Obs.)
NH-ACME_F	Same as NH-ACME_P	Sam as NH-ACME_P, except for the future period	AMIP-type with Obs. + Δ(SST+sea ice)
NH-ACME_NU	Same as NH-ACME_F	Same as NH-ACME_F	Same as NH-ACME_F, except with the present-day urbanization

The second step is to evaluate the fidelity of the NH-ACME model employed to examine the future ST changes (Fig. 4). The evaluation will focus on (a) the general nature of the major mechanisms impacting ST occurrence and intensity gained from the process-level understanding in Step 1, (b) observed ST characteristics from the robust observations, and (c) the occurrence and burned area of wildfires to understand the model capability in simulating wildfires. As described above, to avoid significant problems associated with using a large-scale environmental index as proxy for STs, I will use the ACME model with a NH dynamical core under development by Dr. Mark Taylor, a collaborator of the proposed work, to conduct RR simulations to explicitly simulate STs in the region of the central and western United States only. The NH-ACME will be available for real-world simulations in 2018 when Dr. Taylor's project ends. Although not likely, if NH-ACME is not ready when this project needs it, the Model Prediction Across Scales (MPAS) in the Community Earth System Model (CESM) (Sakaguchi et al. 2015; Zhao et al. 2016) will be the backup choice. This model with a variable resolution of 3-km over the tropics has been used for short-time simulations in Pilon et al. (2016). Chun Zhao at PNNL has also conducted simulations using MPAS-CESM at 4-km over CONUS (personal communication).

For a GCM with RR grids to perform well on convection, scale-aware cumulus parameterizations are necessary. The CLUBB scheme has shown promising scale-awareness at resolutions of 2-16 km (Larson et al. 2012). Therefore, I will employ the CLUBB unified parameterization (Thayer-Calder et al. 2015) that is for all cloud types including deep convection. This version of the ACME model is on an ACME branch and being further developed by our CMDV project as discussed in Section 2.2.

As computing power increases, it may be feasible to run a RR grid higher than a 3 or 4 km resolution in the next few years. The goal of NH-ACME simulations is to capture the major physics-dynamic interaction mechanisms associated with STs, so the results from the WRF simulations at different resolutions will guide us to choose an appropriate RR grid spacing. I want to emphasize that the target in GCM simulations is not a very fine-scale ST feature such as tornado touchdown and hailstone size, but these supercell storm characteristics that have a larger scale than tornado touchdown and hailstone size.

The simulations for the present period (i.e., NH-ACME_P in Table 1) will be run with the observed SSTs and sea ice boundary conditions but allowing atmosphere-land interactions (i.e., the Atmospheric Model Intercomparison Project (AMIP) simulations), to more realistically simulate the present climate. Initial conditions will be provided by ACME's fully coupled simulations, part of the ACME biogeochemical cycle experiments that cover the period from pre-industrial to 2100, with a grid resolution of 1 degree. These simulations will be performed by the ACME team and released for community use. To save computing time, I plan to run such RR simulations focused over the western and central United States (including states like Tennessee and Alabama) for spring and summer seasons only because STs mainly occur in the CUS warm season. The simulation time period will be informed by the statistical analysis of long-term observational data. Based on literature studies using 10-yr time period (e.g., Trapp et al. 2011, Gensini and Mote 2015), I will start with 10-year data (2006-2015) and conduct statistical significance tests on results. I will expand to a longer time period, if necessary, until statistical significance is achieved. To evaluate the NH-ACME_P, observational data will be analyzed to help understand ST behaviors (see Task 2a for details). The work in this step will achieve Objective #2.

The RR configuration at a convection-permitting scale is more computationally feasible than at global uniform resolution of a few km, and allows explicit ST simulations to avoid using the large-scale environmental index as a proxy for STs. Also, the RR approach should be superior to the regional downscaling approach (e.g., Trapp et al. 2011) because it allows more realistic interactions between mesoscale/storm-scale processes and large-scale circulations such as the middle-latitude trough and subtropical high. The estimate of the core hours for each half-year simulation is about 0.25 million, based on 0.5 million per simulation year for CESM with the MPAS at 4-km resolution focused over CONUS with 30 vertical layers (personal communication with Chun Zhao of PNNL).

In the last step (Step 3 in Fig. 4), I will perform NH-ACME RR simulations for a future period (i.e., NH-ACME_F in Table 1) with the Representative Concentration Pathways (RCP) 8.5 to represent the GHG emission scenario for a larger climate change signal (the so-called business-as-usual). The time period will have the same length as in Step 2 with 2100 as the end year (if 10-yr is used in Step 2, then the future period is 2091-2100). To compare with NH-ACME_P in which observed SST and sea ice are used, NH-ACME_F will be run with the same RR grid but with mean monthly perturbations of SSTs and sea ice (Δ(SST+ sea ice)) added to the observed SST and sea ice distribution. The Δ (SST+ sea ice) will be calculated as the difference between the mean monthly values in the future period and the present period from the ACME coupled simulation following the RCP8.5 scenario. To better account for land-use and emission changes from urbanization, I will use the integrated assessment scenarios based on the Shared Socioeconomic Pathway (SSP) 5, which is a fossil-fuel development scenario with a population more than double the present (hence larger urbanization). The SSP provides projections of future energy production and use, land-use changes, and GHG emissions and atmospheric concentrations accounting for urbanization. I will take advantage of the downscaled SSP scenarios over CONUS based on SSP5 that will be available through a project on "A hierarchical evaluation framework for assessing climate simulations relevant to the Energy-Water-Nexus" (PNNL PI: Ruby Leung). Given the large uncertainty in projecting future climate caused by scenario and model uncertainties and internal variability, multi-model ensemble simulations are needed for more robust results. However, given my focus on process understanding, a very high-resolution modeling approach is imperative, which limits the length and number of simulations. Convection-permitting simulations capable of representing ST characteristics with a single model can provide significant insights far beyond our current understanding derived from modeling of large-scale environment alone.

I will examine how future human activities influence the subtropical high and the mid-latitude trough, and the major mechanisms for impacts of land surface, aerosols, and precipitation, and how these changes subsequently alter ST occurrence, intensity, and spatial distribution from the present to future period to answer Q2 and Q3. To separate the contribution by future urbanization from future climate warming as stated in Q3, I will conduct sensitivity simulations for the future period with present-day urbanization (i.e., NH-ACME_NU in Table 1). Through the investigations in this step, I will achieve a third objective of more robust understanding of how ST characteristics will change in future over the CUS by considering the compounding changes of climate warming and urbanization and their relative contributions.

The unique aspects of the proposed approach include (1) the use of the most advanced process-level modeling system with bin cloud and aerosol models to provide the best possible modeling dataset for process understanding; (2) the use of new ACME model framework advances (i.e., NH-ACME), which not only allows explicit representation of the interactions between the large-scale environment and mesoscale/storm-scale processes, but also avoids the uncertainty associated with using an environmental index for quantification of the change of ST. No past studies on ST changes in a future climate has addressed these two problems simultaneously.

3.2 Major tasks

Task 1: Process-level understanding of STs

1a. Case selection, model updates and developments, and simulation designs

We will select STs based on Doppler radar measurements from the Next-Generation Radar (NEXRAD) network and surface observations of hail and tornado data from the NSPC to focus on cases in recent years (after 2000). In particular, we will select ST cases from DOE ARM-supported field campaigns of the MC3E and Plains Elevated Convection at Night (PECAN) where the multi-Doppler measurements (e.g., ARM C-band and X-band radars and NEXRAD) are available, which will help us gain better understanding of storm structure and intensity (Fan et al. 2015b; 2016b). Several ST cases will be selected with possible influence by wildfires over the Rocky Mountains, the mountains further west, and the Central America, respectively. We will examine MODIS images and aerosol optical depth measurements as well as the wind field data from NCEP final reanalysis data, and also run the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model to determine whether a case is possibly under the influence of wildfires from one of the three regions. For urbanization, we will select several STs that produce a significant number of tornado or hailstones cases over urban areas such as Oklahoma City, Kansas City, Dallas and their nearby cities.

Numerous WRF/WRF-Chem simulations will be conducted in Task 1 for studying impacts of wildfires, urbanization and feedback of precipitation. Here I only use wildfires as an example to describe the simulation design, since others will follow the similar designs. We will use the latest release of WRF/WRF-Chem (i.e., v3.8.1), in which CLM4.0 is coupled (Zhao et al. 2014). We will update CLM4.0 with CLM4.5 or higher to incorporate state-of-art developments in land-surface processes (Oleson et al. 2013). Although CLM4.5 or higher in CESM includes the most state-of-art fire model developments (Li et al. 2012a,b, 2013), the fire model is not applicable to high-resolution WRF and WRF-Chem simulations (personal communication with Prof. Xiaohong Liu at the University of Wyoming). Therefore, in studying impacts of wildfires in WRF-Chem simulations, we will use prescribed fire emissions and land-cover change based on the satellite-based Global Fire Emission Database Version 4 (GFED4) at 0.25 degree (Giglio et al. 2013), which is available from 1997 through the present. The flame temperature will be prescribed with values based on measurements for different types of flames (Audoin et al. 1995). With the above configurations, all three factors (i.e., land surface, emissions and T) changed by wildfires can be accounted. We will run a benchmark simulation with WRF-SBM-MOSAIC for each selected wildfire case with all three factors considered (WRF_BASE in Table 1), then conduct sensitivity simulations (WRF_SENS) by turning off the fire emissions, without changing land-surface type, without changing T, or without all three changes, respectively, to examine the effect of each of three factors and the overall effect of wildfires.

To study the role of urbanization in ST characteristics, we will run a WRF_BASE simulation for each case using WRF-SBM-MOSAIC (WRF_BASE). Similarly, a set of sensitivity tests (WRF_SENS) will also be performed in which both the urban land is replaced with grass land in CLM and the anthropogenic emissions over the urban land is turned off, or one of them is changed, to examine the major mechanisms and single out the respective effects of the two factors.

All WRF/WRF-Chem simulations will use the initial and boundary conditions from NCEP Final Analysis at 1^o spatial resolution or regional reanalysis data such as the NCEP North American Regional Reanalysis (NARR) (depending on the cases). Many studies have used NCEP data at 1^o or even 2.5^o to drive WRF high-resolution simulations (e.g., Trapp et al., 2011; Fan et al. 2015b).

1b. Study the mechanisms of how wildfires impact STs. We will run and extensively evaluate WRF_BASE for each case with observations from surface meteorological measurements (including precipitation rate), sounding, Doppler radar, etc. The benchmark simulations along with observations will allow us to understand the physical and aerosol environments of the studied STs. We will explore the mechanism of how wildfires in each of the three regions impact storm initiation, severity, and location change. WRF_SENS simulations will be run and analyzed to support the mechanisms and examine the relative contribution of each of the three pathways. For aerosol impacts, we will further analyze the respective contributions of ACI and ARI by turning off ARI in a sensitivity test. The analysis will mainly focus on how the thunderstorm is initiated and evolves, and how the CAPE and lower-level shear and humidity, which are keys to escalating a typical thunderstorm to a supercell thunderstorm, are changed by various processes.

1c. Study the mechanisms of how urbanization impacts STs. We will study two groups of ST cases here: those initiated over the urban areas and those initiated over non-urban areas but intensified over the urban areas, to study the impacts of urbanization on storm initiation and intensification. The overall effect and the major mechanisms will be explored by comparing the WRF_BASE with the WRF_SENS in which the urban land is replaced with grass land and anthropogenic emissions over the urban land are turned off. The respective effect of each factor will be obtained by analyzing the WRF_SENS with only one factor changed. Some ST cases could be affected by both wildfires and urban land. For those cases, following the same methodology as in Tasks 1b and 1c, we will study the joint effects of wildfires and urbanization and their respective importance.

1d. Study the feedback of extreme precipitation to subsequent STs. This feedback could be important for summer when the soil is generally drier relative to spring. To explore the potential relationships between extreme precipitation and subsequent ST formation and intensity through the feedback to soil moisture over this region, we will conduct independent modeling and observational analyses. For observational study, we will analyze the data from the North American Soil Moisture Database (NASMD; Quiring et al. 2016), which is a quality-controlled soil moisture dataset comprised of many soil moisture observation networks including Oklahoma Mesonet sites (OK Mesonet), and examine the pre-storm conditions focusing on soil moisture conditions for STs over a decade-long period (2006-2015) or longer if needed for statistical significance. This is to understand if there is any significant observed relationship between soil moisture and ST occurrence or intensity. If we observe statistically significant relationships, then we will conduct high-resolution WRF simulations for case studies to examine the detailed mechanisms following the similar experiment designs in Task 1b-1c. For the purpose of this investigation, we will simulate the ST cases that have very high soil moisture conditions or large soil moisture contrast between wet and dry soils in their pre-storm environments, which are often associated with precipitation from a previous storm event.

1e. Scale-dependencies of the ST characteristics and major mechanisms. At least one representative case from each of the investigations of 1b-1d will be selected for the WRF_RES simulations. By analyzing WRF_RES along with WRF_BASE, we will gain understanding of the scale-dependencies of the ST characteristics and the associated major interaction mechanisms, to better inform the choice of the RR grid spacing for NH-ACME simulations in the following steps and better understand the uncertainties of NH-ACME simulation with the selected RR grid in simulating ST characteristics.

Task 2: Evaluate NH-ACME RR simulations over the present period

2a. Model update and development. The ACME atmosphere model began as a fork of the Community Atmosphere Model (CAM) (version 5.3.83, Neale et al., 2012), the atmospheric component of the CESM. PNNL played essential roles in the development of CAM5. ACME has the latest CAM5 component in CESM, such as the CLUBB parameterization for shallow convective processes (Golaz et al. 2002; Larson et al. 2002; Bogenschutz et al. 2013), and an improved Morrison-Gettelman microphysics (MG2) that includes a prognostic treatment for rain and snow, and a few modifications to the droplet nucleation and time-step algorithm (Gettelman et al. 2015; Gettelman and Morrison 2015). ACME further revised the ice microphysics to better account for ice formation using Classical Nucleation Theory (Wang et al. 2014) and impacts of pre-existing ice particles (Shi et al. 2015). The three-mode CAM5 aerosol formulation described in Liu et al. (2012) was also revised to include a fourth mode (Liu et al. 2016) to allow explicit aging of carbonaceous aerosol species. Vertical resolution has been increased from 30 layers in CAM5 to 72 layers in the ACME model and the upper boundary is extended from ~40 to 64 km with much higher resolution near the surface.

The current ACME has a branch with the CLUBB unified parameterization for all cloud types, including deep convection (Thayer-Calder et al. 2015). CLUBB relates the turbulent length scale to the horizontal grid spacing, which makes the scheme have a scare-aware factor (Larson et al. 2012). Therefore, we will employ the CLUBB unified scheme in the ACME simulations for this project. A few projects at PNNL such as the ACME Science Focus Area (SFA) and CMDV are further developing the ACME model. The ACME SFA aims to improve simulations at higher resolution up to 10 km, and our CMDV project is targeting MCS simulations in GCMs by improving convection and microphysics parameterizations. As described in Section 2.2, we are further improving the scale-awareness of the CLUBB unified scheme in the CMDV project. I will coordinate with those projects to ensure I am using the latest version of the ACME code.

Currently, CLM4.5 has been incorporated with ACME and it is likely to be updated with the latest version of CLM for the ACME SFA. The fire model in CLM4.5 and higher is state-of-art and can reasonably simulate the satellite-observed global total temporal variability and large-scale spatial pattern of burned area and fire emissions (Li et al. 2014). However, fire dispersion is not yet considered. We will incorporate the plume dispersion model following Freitas et al. (2007; 2009) in ACME to better simulate the transport of heat, water vapor, and aerosols by fire plumes.

2b. NH-ACME RR configurations and simulations. Configuring the NH-ACME RR at a convection-permitting scale is a time-intensive, multi-step process involving the creation of input files unique to each grid that contains, for example, topography, land cover and properties, emissions, winds, and fluxes. This process ensures the general circulation of the atmosphere is balanced so that spurious gravity waves are not excited. A postdoc will be hired to work on this aspect of the project, and he/she will work with my collaborator Dr. Erika Roesler at SNL to gain the training. The three sets of NH-ACME simulations will be conducted as shown in Table 1 and are discussed in Section 3.1.

2c. Statistical analysis of long-term observations. To evaluate the performance of NH-ACME in simulating ST occurrence and intensity for the present period, it is important to use unique observational datasets such as Doppler radar and ARM long-term observations which are only available for the recent 1-2 decades. Since tornadoes or hailstone sizes might not be well simulated even with a RR grid of ~ 3 km, to use consistent criteria between observations and simulations for evaluating ST characteristics, STs will be identified based on the criteria with a threshold for the hourly UH integrated over the 2–5 km layer above ground level representing rotating updraft cores and for radar reflectivity (Ze), respectively. Different threshold values for UH and Ze have been used between Trapp et al. (2011) and Gensini and Mote (2014). We will test different pairs of UH/Ze values using fractional gross error and mean bias statistics to determine the most appropriate thresholds for ST occurrence following Gensini and Mote (2014). ST intensity can be assessed based on the magnitudes of UH and Ze values. The PDFs of ST intensity will be analyzed and we will separate our analysis for spring and summer, respectively. The spatial distribution of the STs will be analyzed. We will obtain recent decadal radar reflectivity data from the NEXRAD. The metrological data for calculating UH observations will be from NARR. As discussed in Section 3.1, we will start with the 10-year period first and conduct statistical significance tests on the observed results.

Besides STs, we will use other datasets to evaluate the model performance such as hourly precipitation data, surface meteorology from soundings and Mesonet, and ARM long-term measurements at SGP site on LWP, precipitation rate, surface radiation, and surface fluxes. We plan to use the hourly precipitation rate data from the Arkansas-Red Basin River Forecast Center (ARBRFC) product. This product has a wide spatial coverage and decadal temporal coverage, combining NEXRAD radar precipitation estimates with rain gauge reports at a horizontal grid spacing of 4 km. We will focus on the comparison of the PDFs of precipitation rates given the nature of STs.

The statistical characteristics of the pre-storm environments will be analyzed using Mesonet data in conjunction with the sounding data from ARM SGP site and other regular metrological stations. ARM has more than two decades of long-term measurements at the SGP site for cloud properties, precipitation, radiation, and surface sensible and heat fluxes, which can be downloaded from the ARM Archive. Those datasets will be analyzed and used to evaluate the NH-ACME performance. To improve understanding and support findings from the process-level studies in Task 1, we will analyze the correlations of ST characteristics with meteorological variables such as CAPE, low-level wind shear and low-level RH, and other environmental factors such as soil moisture content and aerosol properties. Multi-variant correlation and regression, and statistical significance tests with the generalized linear model (GLM) will be conducted to extract the significant physical variables and factors based on the observational analysis. Such observational analysis on the significant physical variables/factors in controlling ST occurrence and intensity will be also used to evaluate the NH-ACME RR simulations.

The GFED4 will be analyzed to compare the fire occurrence, burned area, and fire emissions between observations and NH-ACME_P simulations to understand if there are significant model biases in simulating wildfires at Central America and the Western United States to better understand model uncertainty in the future-period simulations.

2d. Evaluation of NH-ACME RR simulations. STs in the NH-ACME RR simulations will be identified using the consistent criteria in UH and Ze with observations as discussed in 2c. The Ze will be calculated offline based on predicted hydrometeor mass and number mixing ratios and the assumed hydrometeor size distribution and density in the microphysics scheme. We will evaluate the performance of NH-ACME_P in: (1) qualitatively reproducing the major mechanisms for the impacts of wildfires, urbanization, and extreme precipitation discovered from the process-level studies conducted in Task 1; (2) reproducing the long-term observed statistical results particularly ST characteristics; and (3) reproducing the observed fire occurrence, burned area, and fire emissions. As for (1), the NH-ACME_P will be analyzed in the same way as outlined in Task 1 and compared. For (2), long-term observations will be analyzed as described right above in Task 2c, and the corresponding analyses will be performed for NH-ACME_P and compared for (a) seasonal and inter-annual variability of ST occurrence and intensity, the spatial distribution of ST occurrence and intensity, and the PDF of ST intensity; (b) PDFs of precipitation rate and radar reflectivity; (c) the statistical characteristics of the pre-storm environments; and (d) the correlations of ST characteristics with meteorological variables such as CAPE, low-level wind shear, and low-level RH, and other environmental factors such as soil moisture and aerosol properties. For (3), we will evaluate the spatial distribution of fire occurrence, burned area, and fire emissions focusing on the western U.S. and Central America using the GFED4 as discussed in Task 2c.

I understand that the above evaluations might show large biases of NH-ACME in some aspects, because of reasons like (1) the RR grid might still not resolve the important small-scale physics-dynamics interactions, (2) cloud physics might be poorly represented such as the MG2 two-moment microphysics scheme in ACME does not well represent ACI, and (3) the fire model might produce significant biases in fire occurrence. In all these cases, evaluation with the process-level understanding from Step 1 will indicate missed information and their associated bias magnitudes, which will be useful as well in understanding GCMs, especially ACME. Such understanding will also help estimate the uncertainties of STs in future climate simulations. As stated in Section 2.2, it is likely that in this research we will use the three-moment cloud microphysics scheme, under development for the ACME model by our CMDV project that I am co-leading, to better simulate microphysical processes and ACI relative to MG2.

Task 3: Study ST characteristics in a future climate

3a. NH-ACME RR simulations over the future period. We will conduct NH-ACME_F and NH-ACME_NU as shown in Table 1, and the designs are detailed in Section 3.1.

3b. Changes of the subtropical high and mid-latitude trough and their major mechanisms. We will examine how dynamics and thermodynamics such as *T*, CAPE, and wind shear, as well as the associated synoptic systems - the mid-latitude trough and the subtropical high pressure system, are changed from the present to future period by future human activities by comparing NH-ACME_F with NH-ACME_P, and analyze the mechanisms responsible for the changes in the CUS. We will also analyze how the human activities change the significances of the major interactive mechanisms for land surface, aerosols, and extreme precipitation impacting STs discovered in Step 1. For example, the feedback of extreme precipitation through soil moisture to ST could be much more significant in the future compared with the present period because of much more extreme precipitation and more severe droughts. The analyses in this task will answer Q2.

3c. Overall changes of ST characteristics, and the respective contributions by future climate warming and urbanization. Following Task 2d for NH-ACME_P, we will conduct the same analysis for NH-ACME_F, and compare with the results from NH-ACME_P to assess the overall changes of ST occurrence, intensity, and spatial distribution from the present to future period. An in-depth analysis will be conducted to explain how the changes occur. We will isolate the effect of the future urbanization by comparing NH-ACME_P with NH-ACME_NU. Then the effect of climate warming (containing the effect of increased wildfires) will be isolated by examining the difference between the overall effect and the urbanization effect. This task will answer Q3.

3d. Statistical analysis for quantifying the change of ST characteristics. It is important to distinguish the true trend from noise. We will calculate statistics such as mean bias (MB), normalized mean bias (NMB), and correlation coefficient (R) for many comparisons such as precipitation, and conduct statistical significant tests for the trends of ST occurrence and intensity. Furthermore, to quantify the changes of PDFs such as PDF of ST intensity and precipitation, we will employ the two-sample Kolmogorov–Smirnov (KS) test (Chakravarti et al. 1967) that has been widely used in hydro-climatic studies to quantitatively compare the PDFs of the present and future time periods following Leng et al. (2016). The KS test returns a decision of true/false for the null hypothesis that two samples are from the same PDF. We will further quantify the respective contributions of PDF moments such as mean, variance, and skewness to the changes of the PDFs following the method of Leng et al. (2016) in using the KS test.

3.3 Personnel and collaboration

As PI, I will spend 50% of my time each year on this project. Two postdoctoral associates (to be recruited) are budgeted each year. One will mainly work on the long-term observational data analysis and the global model configuration, simulations, and analysis, and the other will work on the studies of STs impacted by wildfires and urbanization focusing on land surface changes. I will be responsible for achieving the objectives of the project and reporting progress to program managers, and oversee all tasks to ensure objectives are achieved on time. I will instruct the postdocs as well as conduct the work of aerosol impacts related to wildfires and urbanization. Drs. Mark Taylor and Erika Roesler at SNL are the collaborators on this project. Dr. Taylor will mainly provide the NH-ACME code and guidance in using NH-ACME. Dr. Roesler will help train a postdoc in ACME RR grid configuration at a convection-permitting scale. I will also collaborate with other scientists working on ACME development, CLM, and downscaled SSP during the course of the project.

3.4 Available resources

Accomplishing the project goals is heavily dependent on computing resources. The project will secure supercomputer time at DOE National Energy Research Scientific Computing Center (NERSC) for NH-ACME RR simulations, and will purchase 12 nodes on the PNNL Institutional Computing (PIC) for WRF/WRF-Chem simulations (that is ~ 10 millions of core hours). If NERSC cannot meet all NH-ACME simulation needs, I will also apply for computing resources from the Argonne and Oak Ridge leadership computing facilities through the DOE Innovative and Novel Computational Impact on Theory and Experiment (INCITE) and ASCR Leadership Computing Challenge (ALCC) programs.

3.5 Research timeline

Table 2 The timeline of the research tasks.

Tasks	**Project year**				
	1	2	3	4	5
Task 1: Process-level understanding of ST					
1a. Case selection, model updates/developments, and simulation designs					
1b. Study the mechanisms of how wildfires impact STs					
1c. Study the mechanisms of how urbanization impacts STs					
1d. Study the feedback of extreme precipitation to subsequent STs					
1e. Scale-dependencies of the ST characteristics and major mechanisms					
Task 2: Evaluate NH-ACME RR simulations over the present period					
2a. Model update and development					
2b. NH-ACME RR configurations and simulations					
2c. Statistical analysis of long-term observations					
2d. Evaluation of NH-ACME RR simulations					
Task 3: Study ST characteristics in a future climate					
3a. NH-ACME RR simulations over the future period					
3b. Changes of the subtropical high and mid-latitude trough and the major mechanisms					
3c. Overall changes of ST characteristics, and the respective contributions by future climate warming and urbanization					
3d. Statistical analysis for quantifying the change of ST characteristics					

APPENDIX 1: BIOGRAPHICAL SKETCH

Jiwen Fan, Research Scientist
Pacific Northwest National Laboratory, Atmospheric Sciences & Global Change Division
509-375-2116; Jiwen.Fan@pnnl.gov

Qualifications Summary:

My research encompasses atmospheric chemistry/aerosols, cloud dynamics and physics, and aerosol-cloud-climate interactions. My most dedicated efforts are on providing better understanding of aerosol effects on thunderstorm clouds by developing and using a variety of tools including models, observational data, and simulators. I have built my leading role in aerosol-cloud-precipitation-climate interactions, as reflected in my 2015 AGU Ascent award for exceptional mid-career scientists. I have published 61 papers with publications in *PNAS*, *Nature-Geoscience*, and *Geophy. Res. Lett.* Eleven of the studies were widely featured by media/news. The total citations are greater than 1610, with a H-index of 22 based on the Web of Science report by Oct 2016 (ResearcherID: E-9138-2011).

Education and Training:

2007 Ph.D., Atmospheric Sciences, Texas A&M University, College Station
2002 M.S. Environmental Engineering, University of Central Florida
1999 M.S. Environmental Science, China University of Mining & Technology (Beijing Campus)
1996 B.S. Chemistry, Hunan University of Science & Technology, Hunan, China.

Research and Professional Experience:

Senior Research Scientist, Pacific Northwest National Laboratory (June 2009 – present)
Adjunct Professor, State University of New York (SUNY) (2011 – present)

- Physical understanding of deep convective clouds and aerosol-cloud interactions through CRM simulations with a bin cloud microphysics in conjunction with observations. Organization of mesoscale convective system (MCS) and aerosol impacts on MCS. Scare-aware cumulus parameterization and aerosol-cloud interactions in cumulus parameterization for regional and global climate models. Aerosols impact on extreme weather events. Improving cloud microphysics parameterizations using modeling tools in conjunction with observations. Dust impacts on West Atlantic Ocean storms by serving as CCN and IN.

Postdoctoral Associate, Pacific Northwest National Laboratory (June 2007 – May 2009)

- Study of environmental factors impacting aerosol-convection relationships. Process-level study of Arctic mixed-phase stratocumulus clouds and the associated ice formation. Aerosol indirect effects on tropical convective clouds and water vapor content transport.

Publications (Selected from the total of 61):

Fan, J., Y. Wang, D. Rosenfeld, X. Liu (2016), Review of Aerosol-Cloud Interactions: Mechanisms, Significance and Challenges, Journal of Atmospheric Sciences, 73, DOI: http://dx.doi.org/10.1175/JAS-D-16-0037.1

Gao, W., **J. Fan**, R. C. Easter, Q. Yang, C. Zhao, and S. J. Ghan (2016), Coupling spectral-bin cloud microphysics with the MOSAIC aerosol model in WRF-Chem: Methodology and results for marine stratocumulus clouds, J. Adv. Model. Earth Syst., 08, doi:10.1002/2016MS000676.

Fan J, D Rosenfeld, Y Yang, C Zhao, LR Leung, and Z Li. 2015b. "Substantial Contribution of Anthropogenic Air Pollution to Catastrophic Floods in Southwest China: AIR POLLUTION TO CATASTROPHIC FLOODS." *Geophysical Research Letters*. 42(14). 6066–6075. DOI:10.1002/2015GL064479.

Chen Q, **J Fan**, S Hagos, WI Gustafson, and LK Berg. 2015. "Roles of Wind Shear at Different Vertical Levels: Cloud System Organization and Properties: EFFECT OF WIND SHEAR ON MCS." *Journal of Geophysical Research: Atmospheres*. 120(13). 6551–6574. DOI:10.1002/2015JD023253.

Liu Y-C, **J Fan**, GJ Zhang, K-M Xu, and SJ Ghan. 2015. "Improving Representation of Convective Transport for Scale-Aware Parameterization, Part II: Analysis of Cloud-Resolving Model Simulations: Improving Cumulus Parameterization." *Journal of Geophysical Research: Atmospheres*. n/a–n/a. DOI:10.1002/2014JD022145.

Fan J, Y-C Liu, K-M Xu, K North, S Collis, X Dong, GJ Zhang, Q Chen, P Kollias, and SJ Ghan. 2015a. "Improving Representation of Convective Transport for Scale-Aware Parameterization - Part I: Convection and Cloud Properties Simulated with Spectral-Bin and Bulk Microphysics: CRM Model Evaluation." *Journal of Geophysical Research: Atmospheres*. DOI:10.1002/2014JD022142.

Lim K-SS, **J Fan**, LR Leung, P-L Ma, B Singh, C Zhao, Y Zhang, G Zhang, and X Song. 2014. "Investigation of Aerosol Indirect Effects Using a Cumulus Microphysics Parameterization in a Regional Climate Model." *Journal of Geophysical Research: Atmospheres*. 119(2). 906–926. DOI:10.1002/2013JD020958.

Fan, J., L. R. Leung, P. J. DeMott, J. M. Comstock, B. Singh, D. Rosenfeld, J. M. Tomlinson, A. White, K. Prather, P. Minnis, J. A., Ayers, Q. Min (2014), Aerosol Impacts on California Winter Clouds and Precipitation during CalWater 2011: Local Pollution versus Long-Range Transported Dust, Atmos. Chem. Phys., 14, 81-101, 2014.

Fan J, LR Leung, D Rosenfeld, Q Chen, Z Li, J Zhang, and H Yan. 2013. "Microphysical Effects Determine Macrophysical Response for Aerosol Impacts on Deep Convective Clouds." *Proceedings of the National Academy of Sciences*. 110(48). E4581–E4590. DOI:10.1073/pnas.1316830110.

Wang, Y., **J. Fan,** R. Zhang, L. R. Leung, and C. Franklin (2013), Improving bulk microphysics parameterizations in simulations of aerosol effects, J. Geophys. Res. Atmos., 118, 5361–5379, doi:10.1002/jgrd.50432.

Fan J, LR Leung, Z Li, H Morrison, H Chen, Y Zhou, Y Qian, and Y Wang. 2012a. "Aerosol Impacts on Clouds and Precipitation in Eastern China: Results from Bin and Bulk Microphysics." *Journal of Geophysical Research*. 117. DOI:10.1029/2011JD016537.

Fan J, D Rosenfeld, Y Ding, LR Leung, and Z Li. 2012b. "Potential Aerosol Indirect Effects on Atmospheric Circulation and Radiative Forcing through Deep Convection: AEROSOL-DEEP CONVECTION INTERACTIONS." *Geophysical Research Letters*. 39(9). DOI:10.1029/2012GL051851.

Li Z, F Niu, **J Fan**, Y Liu, D Rosenfeld, and Y Ding. 2011. "Long-Term Impacts of Aerosols on the Vertical Development of Clouds and Precipitation." *Nature Geoscience*. 4(12). 888–894. DOI:10.1038/ngeo1313.

Synergistic Activities (selected):

- 2015 American Geophysical Union (AGU) Ascent award for exceptional mid-career scientists
- 2014 Ronald L. Brodzinski Award for Early Career Exceptional Achievement
- AMS Atmos. Chem. Committee (2012-present) and AGU Publication Committee (2010-2012; 2012-2014).
- Chair or Co-chair of the AMS Symposiums on Aerosol-Cloud-Climate Interactions in 2013, 2014, 2015, 2016, 2017
- Chair of AMS Atmos. Chem. Committee (2014-2017); Chair the Editor-in-Chief Search Committee for J. Adv. Model. Earth Syst. (JAMES) in 2014.

Collaborators and Co-editors:

Collaborators: Collis, Scott (ANL), Comstock, Jennifer (PNNL), DeMott, Paul (CSU), Dong, Xiquan (UND), Fast, Jerome (PNNL), Ghan, Steve (PNNL), Giangrande, Scott (BNL), Heymsfield, Andy (NCAR), Kollias, Pavlos (Stony Brook U.), Leung, Lai-Yung (Ruby) (PNNL), Li, Zhanqing (U. Maryland), Lim, Kyo-Sun (PNNL), Machado, Luiz (INPA, Brazil), Martin, Scott (Harvard), Mei, Fan (PNNL), Min, Qilong (SUNY), Morrison, Hugh (NCAR), Prather, Kim (UCSD), Qian, Yun (PNNL), Rosenfeld, Daniel (Hebrew U. of Jerusalem), Varble, Adam (Utah), Wang, Yuan (NASA/JPL), Wang, Zhien (U. Wyoming), Xu, Kuan-Man (NASA), Yang, Qing (PNNL), Zhao, Chun (PNNL), Zhang, Guang J. (Scripps), Zhang, Yang (NCSU).
Co-editors/co-chairs: Andreae, Meinrat (MPIC, Germany), Collet, Jeff (CSU), Jobson, Tom (WSU), Kreidenweis, Sonia (CSU), Machado, Luiz (INPA, Brazil), Martin, Scott (Harvard).

Graduate and Postdoctoral Advisors and Advisees:

Advisors: Zhang, Renyi (TAMU), Comstock, Jennifer (PNNL), Ovchinnikov, Mikhail (PNNL).
Advisees: Yuxing Yun, K.-S. (Sunny) Lim, Yi-Chin Liu, Wenhua Gao, Bin Han, Jing Yang, Yan Yang, Chen Qian, Yuan Wang, and Hsiang-He Lee

Appendix 2: Current and Pending Support

Jiwen Fan

Current Support:

Supporting Agency: Department of Energy, Office of Science, Biological and Environmental Research (OBER)
Award Number: KP1701000/57131
Project Title: Atmospheric System Research
Project PI: Jerome D. Fast
Investigator Months per Year: 2.0 months
Award Amount: $15,202,793
Award Period: 10/01/2012 to 09/30/2018

Supporting Agency: DOE Office of Science, Office of Science, OBER
Award Number: KP1701000/63041
Project Title: Water Cycle and Climate Extreme Modeling SFA
Project PI: Ruby Leung
Investigator Months per Year: 3.3 months
Award Amount: $7,783,145
Award Period: 10/01/2016 to 09/30/2019

Supporting Agency: Department of Energy, Office of Science, OBER
Award Number: KP1701030/68928
Project Title: Use of remote sensing and in-situ observations to develop and evaluate improved representations of convection and clouds for the ACME model
Project PI: Steven Ghan/Jiwen Fan
Investigator Months per Year: 6.0 months
Award Amount: $8,838,873 (total proposal including all collaborators)
Award Period: 08/01/16 to 07/31/19

Pending Support:

None

Similarities and/or Differences of this Proposal to a Similar Research Proposal Submitted to an Early Career Program at another Agency or Foundation

- No

Note: *Upon notification of Early Career Research Program funding, all support will be reviewed and redirected as appropriate to meet the obligations of the currently proposed effort.*

APPENDIX 3: BIBLIOGRAPHY AND REFERENCES CITED

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APPENDIX 4: FACILITIES AND OTHER RESOURCES

This project will rely heavily on computing resources. A range of resources is available to accomplish the project goals. We anticipate having allocations on the following computing resources:

- *PNNL Institutional Computing (PIC).* Constance is a supercomputer supported through the PIC program for project use across the laboratory. Reasonably sized allocation requests (into the millions of hours) are granted free of charge to projects, with the additional capability provided to buy-in to the cluster for larger projects and higher queue priority. We anticipate a large portion of our development work will be done on this machine due to easy access and a user-friendly development environment for code development. Constance currently has 300 nodes, each with dual-socket 12-core Intel Haswell-based processors, resulting in 7200 processor cores, 64 Gb of memory and 480 Gb of solid state disk. Each node is connected via a Fourteen Data Rate (FDR) Infiniband network. Data storage is provided with a 3.5 PB Lustre-based parallel file system, a 750 TB Isilon Network File System (NFS) appliance, and a 3 PB tape system. While access to this cluster is free, throughput is greatly enhanced by purchasing additional dedicated nodes. This project is therefore purchasing 17 compute nodes, providing 2.5M dedicated core hours per year.
- *NERSC supercomputers.* DOE's NERSC competitively offers computing resources to DOE-funded projects. NERSC's resources include large supercomputers Edison (a Cray XC30 with > 2 PFlops peak performance) and Cori (a Cray based on Intel Many Integrated Core processors with anticipated peak performance > 10 PFlops, to be installed mid-2016). I will write a proposal in September 2017 for application of computing resources.

In addition, this research is eligible for applying for computing resources from the Argonne and Oak Ridge leadership computing facilities, Mira and Titan. I will write a proposal responding to the annual call of Innovative and Novel Computational Impact on Theory and Experiment (INCITE) and ASCR Leadership Computing Challenge (ALCC) programs to apply for the resources. Those programs award to high-risk, high-payoff simulations.

APPENDIX 5: EQUIPMENT

To secure computing resources for the WRF and WRF-Chem model simulations, we propose to purchase 10 compute nodes on Constance, a supercomputer supported through the PIC program for project use across the laboratory. While access to this cluster is free, throughput is greatly enhanced by purchasing nodes. Each node has dual-socket 12-core Intel Haswell-based processors, resulting in 7200 processor cores, 64 Gb of memory and 480 Gb of solid state disk. Each node is connected via a FDR Infiniband network. Data storage is provided with a 3.5 PB Lustre-based parallel file system, a 750 TB Isilon NFS appliance, and a 3 PB tape system. The 17 dedicated notes will provide 13.6 M core hours at a cost of about $81,740.38.

APPENDIX 6: DATA MANAGEMENT PLAN

A sound data management plan is essential to ensure reproducibility of research. The project involves data from various observational data, computer code used to produce model results, and model results. The locations of all of these are clearly defined as below.

Data used to generate the WRF high-resolution simulations that will be mainly performed on PNNL PIC will come primarily from public sources, such as the NCEP analysis and reanalysis data (http://www2.mmm.ucar.edu/wrf/users/download/free_data.html). However, the model data from WRF and WRF-Chem simulations will be stored in a project portal at NERSC that is available to public, where the ACME RR simulations will be performed. History from the ACME RR simulations, as well as the analyzed initial conditions and winds used to initialize and constrain the simulations, will also be stored in the project portal at NERSC (https://portal.nersc.gov/). Data formats within the project will primarily be Network Common Data Form (NETCDF), and will typically follow either the Climate and Forecast convention or the ARM convention within the NETCDF files.

Code for WRF and WRF-Chem simulations will be stored on the PNNL computer Constance and will be available upon request. I will coordinate with the ACME development team about which version of ACME will be used and the ACME code will be stored in an ACME Github branch. The code can be accessed through ACME model releases or ACME collaboration agreement.

APPENDIX 7: OTHER ATTACHMENTS

7.1 Laboratory Director Letter

Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by **Battelle** *Since 1965*

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November 4, 2016

Dr. Renu Joseph
Biological & Environmental Research
U.S. Department of Energy, SC-23
1000 Independence Ave., SW
Washington, DC 20585-1290

Dear Dr. Joseph:

Contract No. DE-AC05-76RL01830 – Early Career Research Program Letter of Support for Dr. Jiwen Fan

I am pleased to provide a letter of support for this proposal submitted in response to LAB 16-1625.

Dr. Fan received her Ph.D. in 2007 from Texas A&M University. Her proposed research, "Understanding Factors Impacting Past and Future Severe Thunderstorms in the Central United States," aligns well with the future directions of the Pacific Northwest National Laboratory's (PNNL) Office of Science program in Modeling the Drivers and Impacts of Extreme Events funded by the Office of Biological & Environmental Research.

If awarded, the proposed project would strengthen PNNL's core capabilities and bring an outstanding early career scientist into an important Office of Science research program.

Sincerely,

SF Ashby

Steven F. Ashby
Laboratory Director

SFA/AAC/jab

U.S. DEPARTMENT OF
ENERGY

7.2 Letter of Collaboration

Sandia National Laboratories

Operated for the U.S. Department of Energy by
Sandia Corporation
P.O. Box 5800
Albuquerque, NM 87185

Dr. Mark Taylor
Principal Member of the Technical Staff
Multiphysics Applications Dept.

November 10, 2016

Dear Dr. Fan,

If your proposal, entitled "Understanding Factors Impacting Past and Future Severe Thunderstorms in the Central United States", is selected for funding under the DOE Early Career Research Program, it is my intent to collaborate in this research by supplying the Accelerated Climate Modeling for Energy (ACME) model with a non-hydrostatic (NH) dynamical core and providing guidance of using the NH-ACME model. Thank you for the opportunity to participate.

Sincerely,

Mark Taylor

Mark Taylor
ACME Chief Computational Scientist

Exceptional Service in the National Interest

Sandia National Laboratories

Operated for the U.S. Department of Energy by
Sandia Corporation
P.O. Box 5800
Albuquerque, NM 87185

November 10, 2016

Dear Dr. Fan,

If your proposal, entitled "Understanding Factors Impacting Past and Future Severe Thunderstorms in the Central United States", is selected for funding under the DOE Early Career Research Program, it is my intent to collaborate in this research by providing guidance in configuring Accelerated Climate Modeling for Energy (ACME) in the regional refinement (RR) framework at a convection-permitting scale, and working with a postdoc during his/her visit at Sandia National Laboratory (SNL) and remotely in providing guidance and support. Thank you for the opportunity to participate.

Sincerely,

Erika Roesler

Erika L. Roesler
Senior Member of the Technical Staff
Department of Atmospheric Sciences
Phone: (505) 284-4925
Internet: elroesl@sandia.gov

Exceptional Service in the National Interest

7.3 Table of Abbreviations

ACI	Aerosol-cloud interaction
ACME	Accelerated Climate Model for Energy
ALCC	ASCR Leadership Computing Challenge
ARBFC	Arkansas River Basin Forecast Center
ARI	Aerosol-radiation interactions
ARM	Atmospheric Radiation Measurement
ASCR	Advanced Scientific Computing Research
BER	Biological and Environmental Research
CAM	Community Atmosphere Model
CAPE	Convective available potential energy
CCN	Cloud condensation nuclei
CESM	Community Earth System Model
CLM	Community Land Model
CLUBB	Cloud Layers Unified By Binormals
CMDV	Climate Model Diagnostics and Validation
CNT	Classical nucleation theory
CONUS	Contiguous United States
CRM	Cloud-resolving model
CUS	Central United States
DCC	Deep convective cloud
DOE	Department of Energy
FNL	Final Analysis
GCM	Global climate model
GFED	Global Fire Emission Database
GHG	Greenhouse gas
GLM	Generalized linear model
HYSPLIT	HYbrid Single-Particle Lagrangian Integrated Trajectory
IOP	Intensive Observation Period
IN	Ice nuclei
INCITE	Innovative and Novel Computational Impact on Theory and Experiment
IPCC	Intergovernmental Panel on Climate Change
KS	Kolmogorov–Smirnov
LAM	Limited-Area Model
LES	Large Eddy Simulation
MCS	Mesoscale convective system
MG2	Morrison-Gettelman microphysics Version 2
MODIS	Moderate Resolution Imaging Spectroradiometer)
MOSAIC	Model for Simulating Aerosol Interactions and Chemistry
MPAS	Model for Prediction Across Scales (MPAS)
NARR	North American Regional Reanalysis
NASMD	North American Soil Moisture Database
NCA	National Climate Assessment
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Center for Environmental Prediction
NERSC	National Energy Research Scientific Computing Center
NETCDF	Network Common Data Form
NEXRAD	Next-Generation Radar
NH	Non-hydrostatic

NOAA	National Oceanic and Atmospheric Administration
NSPC	NOAA Storm Prediction Center
NSSL	National Severe Storms Laboratory
PBL	Planetary Boundary layer
PDF	Probability density functions
PECAN	Plains Elevated Convection at Night
PI	Principal Investigator
PIC	PNNL Institutional Computing
PLACE	Parameterization for Land-Atmosphere-Cloud Exchange
PNNL	Pacific Northwest National Laboratory
RCP	Representative Concentration Pathways
RR	Regionally-refined
SBM	Spectral bin microphysics
SFA	Science Focus Area
SGP	Southern Great Plains
SNL	Sandia National Laboratory
SOA	Secondary organic aerosols
SSP	Shared Socioeconomic Pathway
SST	Sea surface temperatures
ST	Severe thunderstorms
T	Temperature
UH	Updraft helicity
UHI	Urban Heat Island
U.S.	United States
USDA	United States Department of Agriculture
WCB	Warm conveyor belt
WRF	Weather Research and Forecasting
WRF-Chem	Weather Research and Forecasting for Chemistry
Ze	Radar reflectivity