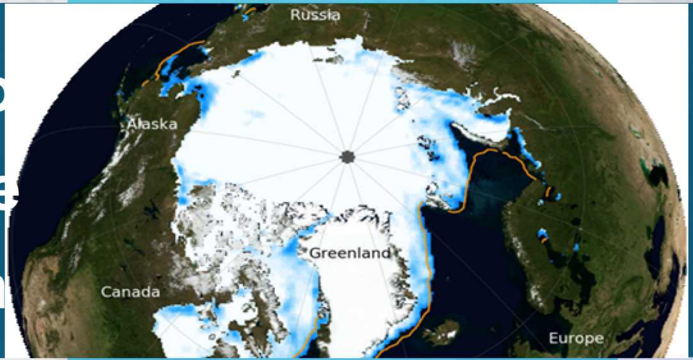
SAND2020-5819C

Using Ultralow Resolution E3SM Simulations to Predict Sea Ice-Free Summers, and to Elucidate the Role of Arctic Sea Ice in Polar Amplification



Speaker: **Amy J. Powell**

Principal Investigator: **Kara Peterson;**
Project Manager: **Mike Parks;**
Arctic Tipping Points Team: **Diana Bull, Warren Davis, Jake Nichol, Matt Peterson, Erika Roesler, David Stracuzzi, Irina Tezaur, Ray Bambha, Jennifer Frederick, Jasper Hardesty, Anastasia Ilgen, John Jakeman, Cosmin Safta**

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ACRONYMS

- **E3SM = Energy Exascale Earth System Model**
- **mULR = mid Ultralow Resolution; ne11 grid; 2.7° x 2.7°, 300 km**
- **PIC = Pre-Industrial Control (*i.e.*, 1850 with no forcings)**
- **QoI = Quantities of Interest**
- **SIE = Sea Ice Extent; area of grid cell covered by at lest 15% sea ice**
- **ULR = Ultralow Resolution; ne4 grid; 7.5° x 7.5°, 834 km**

OVERVIEW

GOALS:

- Deliver climate-realistic ULR configuration for E3SM
- Define class of climate problems that can be addressed at ULR
- Further understanding of sea ice evolution in the context of global climate change

BACKGROUND:

- Arctic sea ice is central to climate stability
- Arctic sea decline as an effect of global climate change

APPROACH:

- Use fully – coupled ULR E3SM simulations to understand sea ice evolution
- Challenges

RESULTS, CONCLUSIONS:

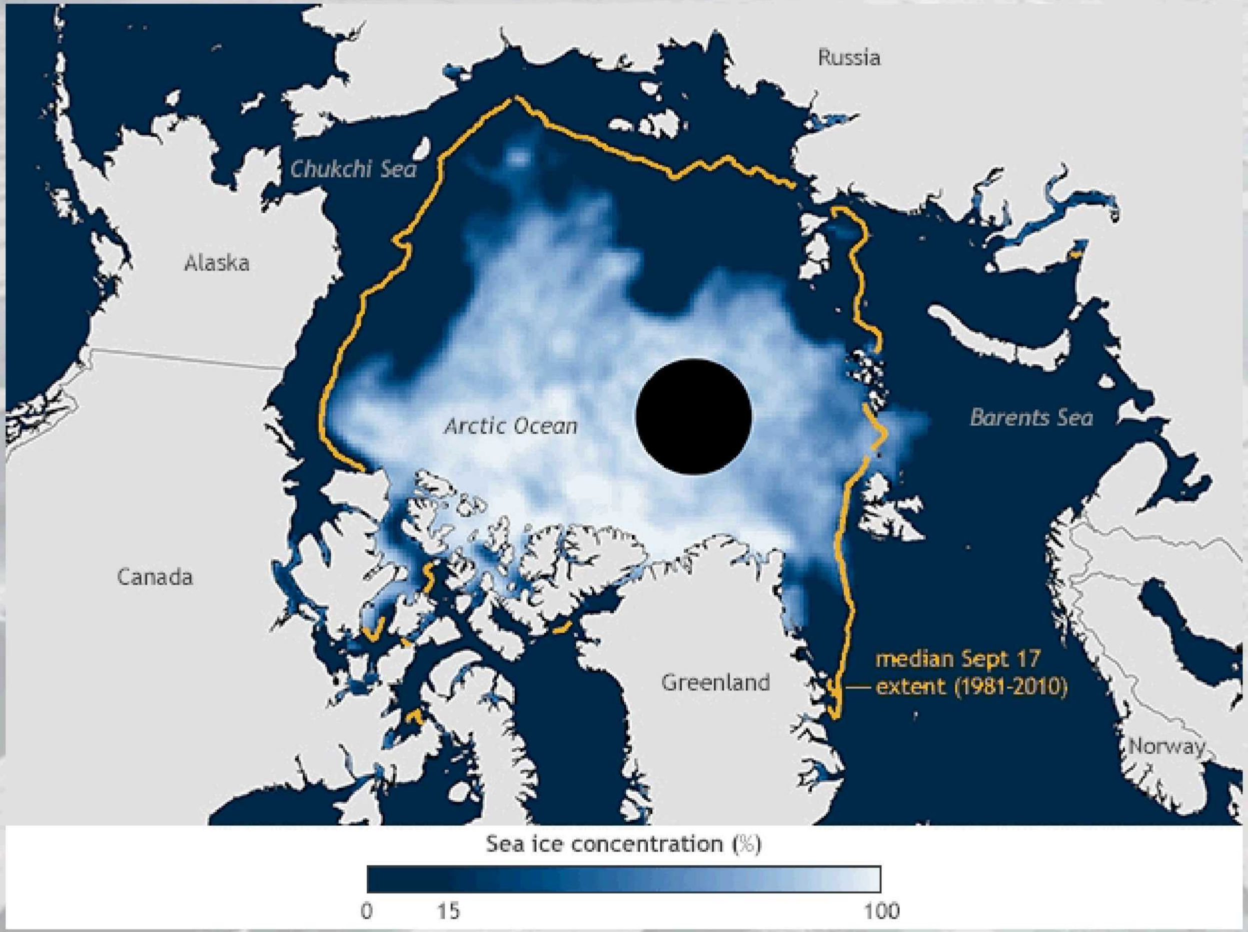
- “Quantities of Interest” (QoI) – based assessments of tuned simulations

NEXT STEPS

ACKNOWLEDGEMENTS

BACKGROUND

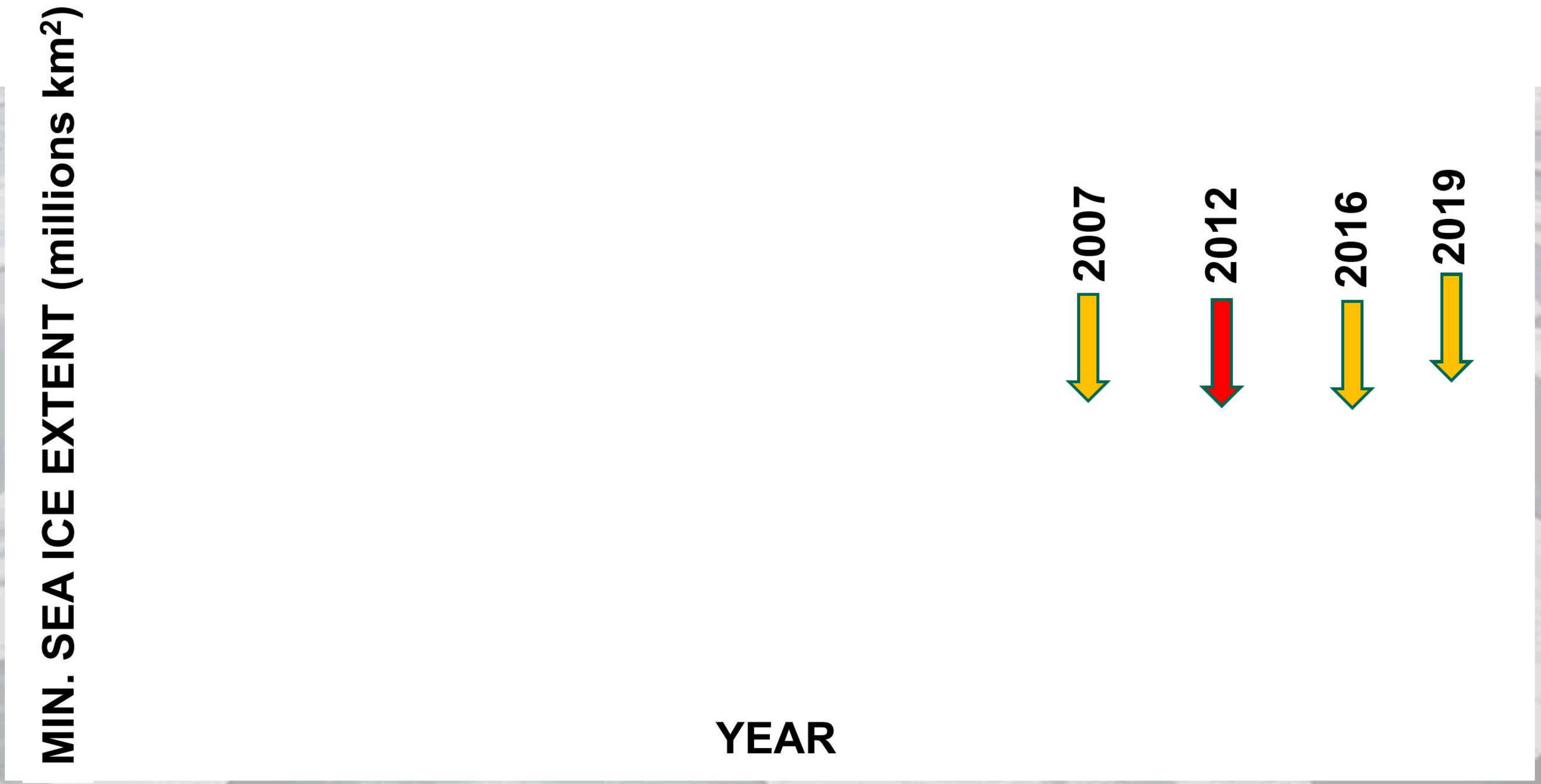
Arctic Sea Ice and Climate



2019 September Sea Ice Minimum *vs*. 1980 – 2010 median (yellow outline)

- Sea Ice extent is a critical control in global climate stability, because sea ice reflects ~ 80% of incoming sunlight
- Sea ice cover in accelerating decline
- Tight coupling of Arctic subsystems – sea and land ice, permafrost, ocean and boreal forests
- Tipping point: Locally irreversible state change for a system
  - Loss of September sea ice
- Tipping of one subsystem (*e.g.*, sea ice), potentially rapidly cascading to others
- Ecological and strategic importance of the Arctic cannot be overstated

Dramatic Sea Ice Decline Since 1980



- Since late 1970s, more sea ice melts annually than forms during winter
- Substantial thinning of perennial (multiyear) ice
- September Arctic sea ice cover rate of decline: 12.85% / decade
- Most significant decreases: 2012, and 2007, 2016, 2019 (three-way tie)
- Large interannual variability in Arctic Sea Ice makes predictive modeling difficult

APPROACH

LEVERAGE ULR E3SM TESTBED SOFTWARE TO DO SCIENCE

- **DEVELOP fully coupled ULR configuration by ”pre-tuning” the model to published values for key atmosphere, oceans, and sea ice parameters in component models to minimize “one at a time” parameter-tuning inefficiencies**

- **RUN E3SM fully-coupled simulations using key comp sets (Pre-Industrial Control, 4XCO2 – forcing) for comparative studies**

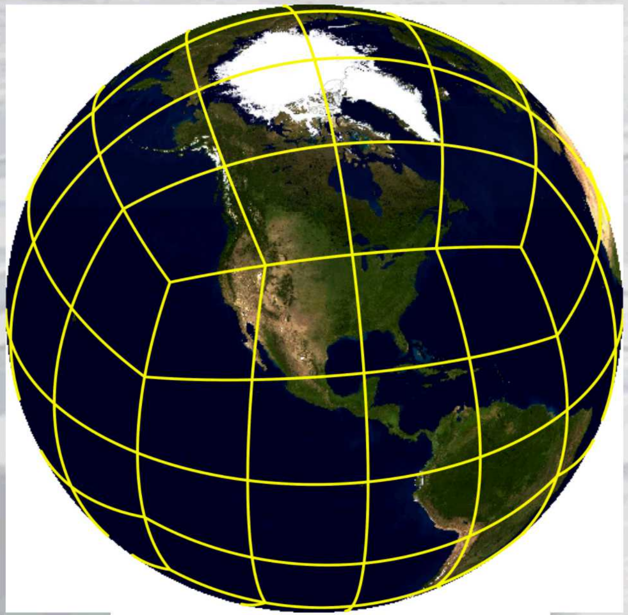
- **ASSESS ULR model fidelity by comparing sea ice-relevant QoI (*e.g.*, sea ice extent, top-of-atmosphere energy flux) in the ULR simulations *vs.* QoI in publicly-available, E3SM 1-degree resolution scientifically-validated datasets**

- **DISCOVER which key physical processes and feedbacks are represented at ULR (~ 250 km^2 /cell sea ice and ocean grid at pole)**

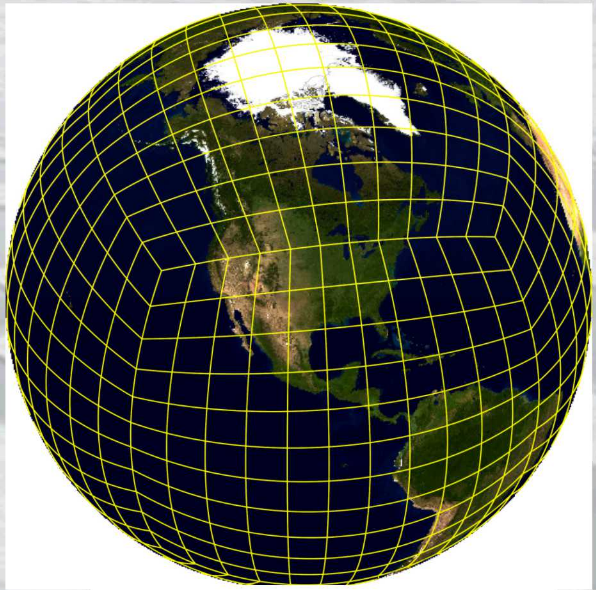
- **EXPLORE large-scale interacting physical processes (including anthropogenic forcing) and internal drivers (*e.g.*, low-frequency Arctic atmospheric variability), main controls on sea ice evolution**

- **Estimate parametric sensitivity and uncertainty for sea ice – related phenomena**

ULTRALOW RESOLUTION IN E3SM – WHAT DOES THIS MEAN?



ne4 Resolution



ne11 Resolution

Resolution	Grid Spacing (equator, km)	Latitude & Longitude Approximation	Physics timestep (s)
ne4	834	7.5 ° x 7.5 °	7200
ne11	300	2.7 ° x 2.7 °	7200
ne30 (standard)	111	1 ° x 1 °	1600

Computing

System	Vendor	Nodes / Cores	Processor	OS	Interconnect	RAM/Node	TFlops	Processor Hours / Year
Skybridge	Cray	1,848/29, 568	2.6 GHz Intel Sandy Bridge:2S:8C	RHEL6	Infiniband	64 GB	600	172, 677,120

- **E3SM Simulations performed on Skybridge**
- **Testbed for the E3SM software engineering Scientific Focus Area**
- **Leveraging these resources as a springboard for Arctic-focused, and broader climate studies**

CHALLENGES

- E3SM is computationally expensive, even at ultralow resolutions
  - ne4 (96 processing elements):
    - Model Cost: 75.29 pe-hrs/simulated_year
    - Model Throughput: 30.60 simulated_years/day
  - ne11 (96 processing elements):
    - Model Cost: 348.52 pe-hrs/simulated_year
    - Model Throughput: 6.61 simulated_years/day
- Complicated "spin up," requiring trial and error tuning for coupled model
- E3SM ULR simulations do not resolve certain important dynamics
  - Baroclinic Instability

RESULTS

MODEL TUNING – Atmospheric Parameters

The DOE E3SM Coupled Model Version 1: Overview and Evaluation at Standard Resolution

Jean-Christophe Golaz[1], Peter M. Caldwell[1], Luke P. Van Roekel[2], Mark R. Petersen[2],
Qi Tang[1], …
David C. Bad…
Marcia Bran…
Philip J. Cam…
Katherine J. …
Brian M. Gri…
Elizabeth C. …
Philip W. Jon…
L. Ruby Leu…
Salil Mahaja…
Renata B. Mc…
J. E. Jack Reeves Eyre[6], William J. Riley[5], Todd D. Ringler[2,17], Andrew F. Roberts[2],
Erika L. Roesler[8], Andrew G. Salinger[8], Zeshawn Shaheen[1], Xiaoying Shi[4], Balwinder Singh[7],
Jinyu…
Milen…
Philli…
Mark D. Zelinka[1], Charles S. Zender[20], Xubin Zeng[6], Chengzhu Zhang[1], Kai Zhang[7],
Yuyin…

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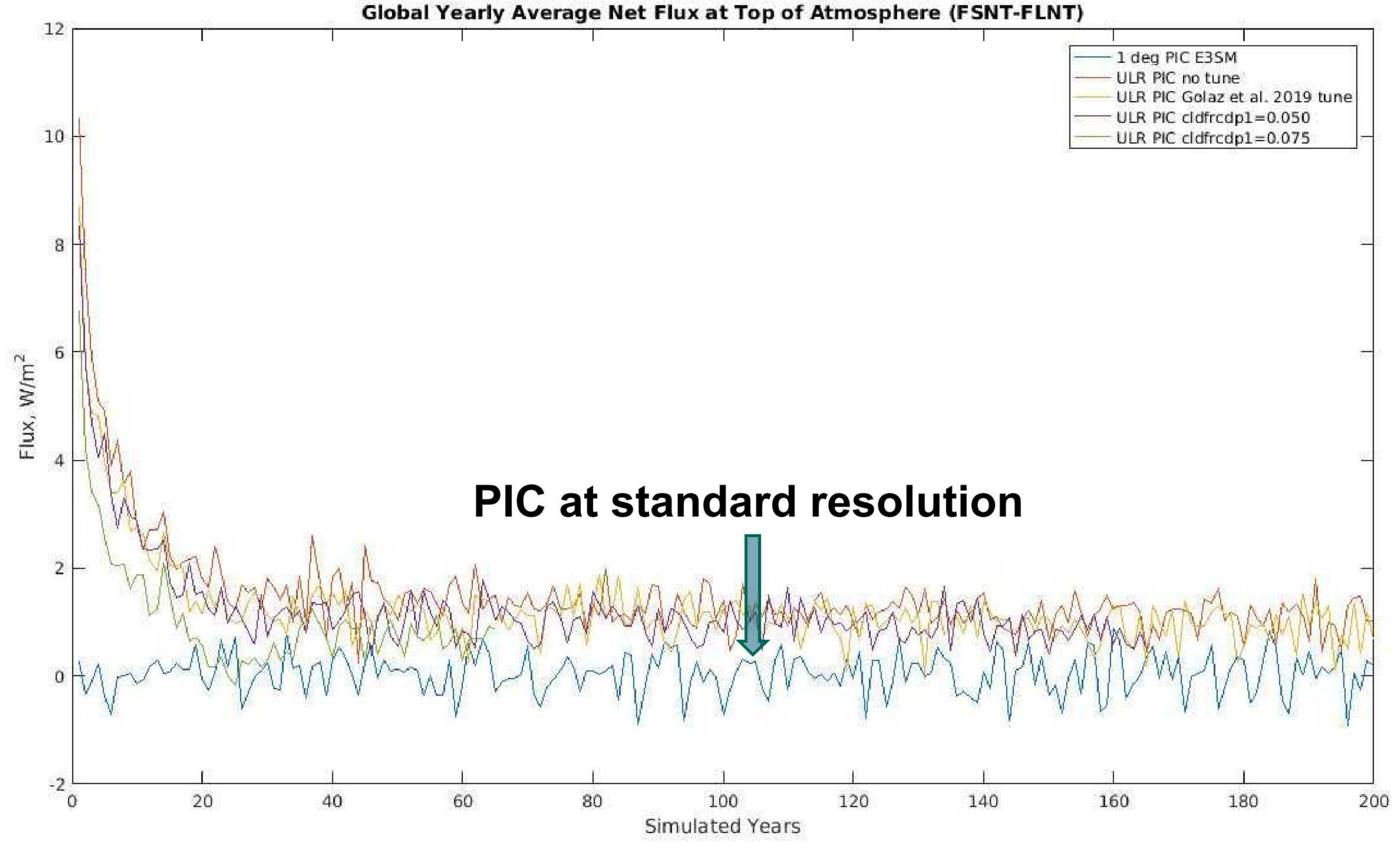
…rows[1],
…H. Wan[1],
…J. Evans[7],
…er[7],
…-H. Yoon[9],
…en[12],

Parametric Sensitivity and Uncertainty Quantification in the Version 1 of E3SM Atmosphere Model Based on Short Perturbed Parameter Ensemble Simulations

Yun Qian[1], Hui Wan[1], Ben Yang[1,2], Jean-Christophe Golaz[3], Bryce Harrop[1], Zhangshuan Hou[1], Vincent E. Larson[4], L. Ruby Leung[1], Guangxing Lin[1], Wuyin Lin[5], Po-Lun Ma[1], Hsi-Yen Ma[3], Phil Rasch[1], Balwinder Singh[1], Hailong Wang[1], Shaocheng Xie[3], and Kai Zhang[1]

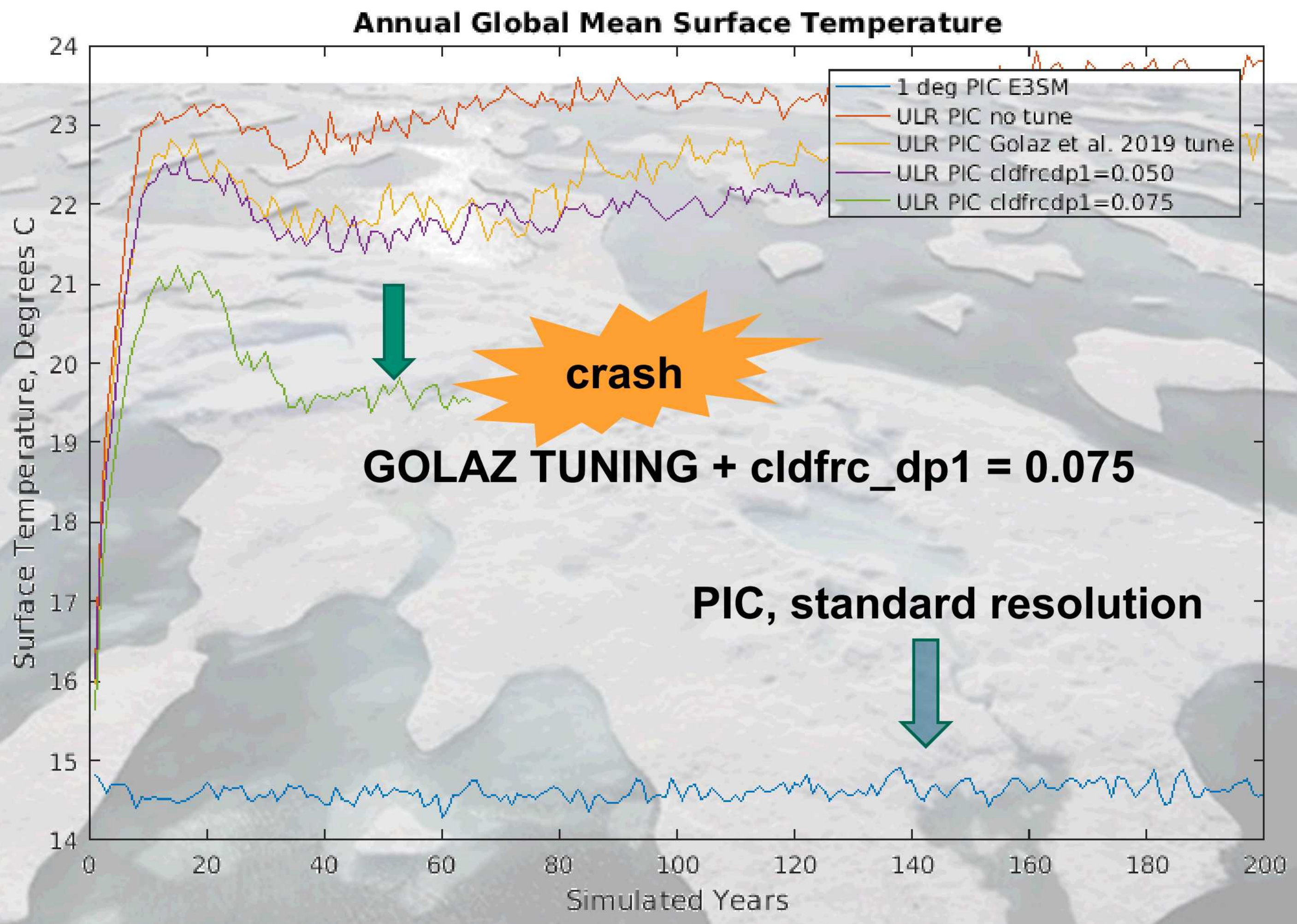
- Recent key references informed our tuning
- Atmosphere component focus (EAM)
- Certain atmospheric tuning parameters show great sensitivity

ULR (NE4) SIMULATIONS – Global Yearly Average Net (Radiative) Flux at Top of Atmosphere QoI with Different EAM Tunings



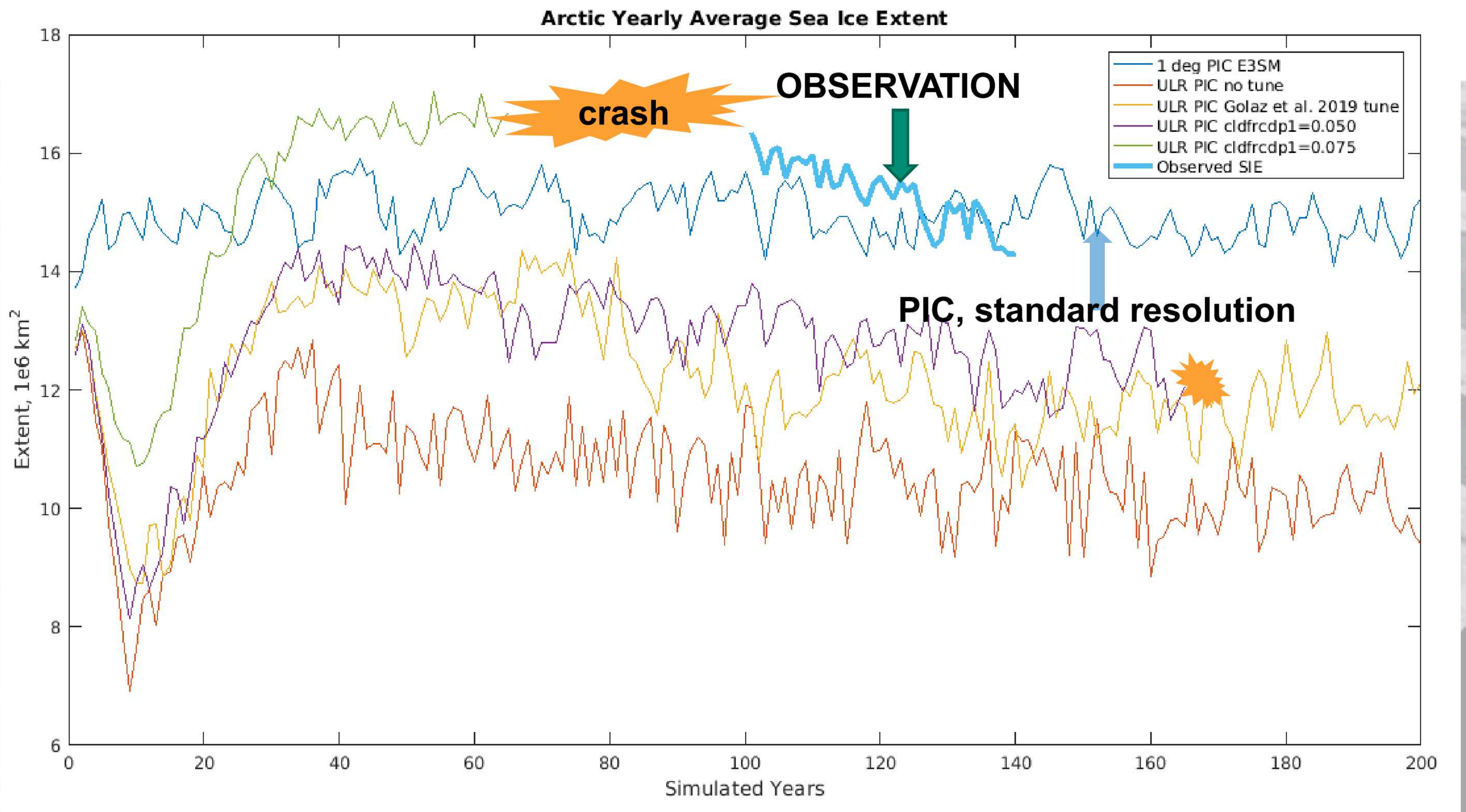
- This QoI is climate realistic *vs* scientifically validated mean
- Various tunings were not significantly different than no tuning

ULR (NE4) SIMULATIONS – Annual Global Mean Surface Temperature QoI with Different EAM Tunings



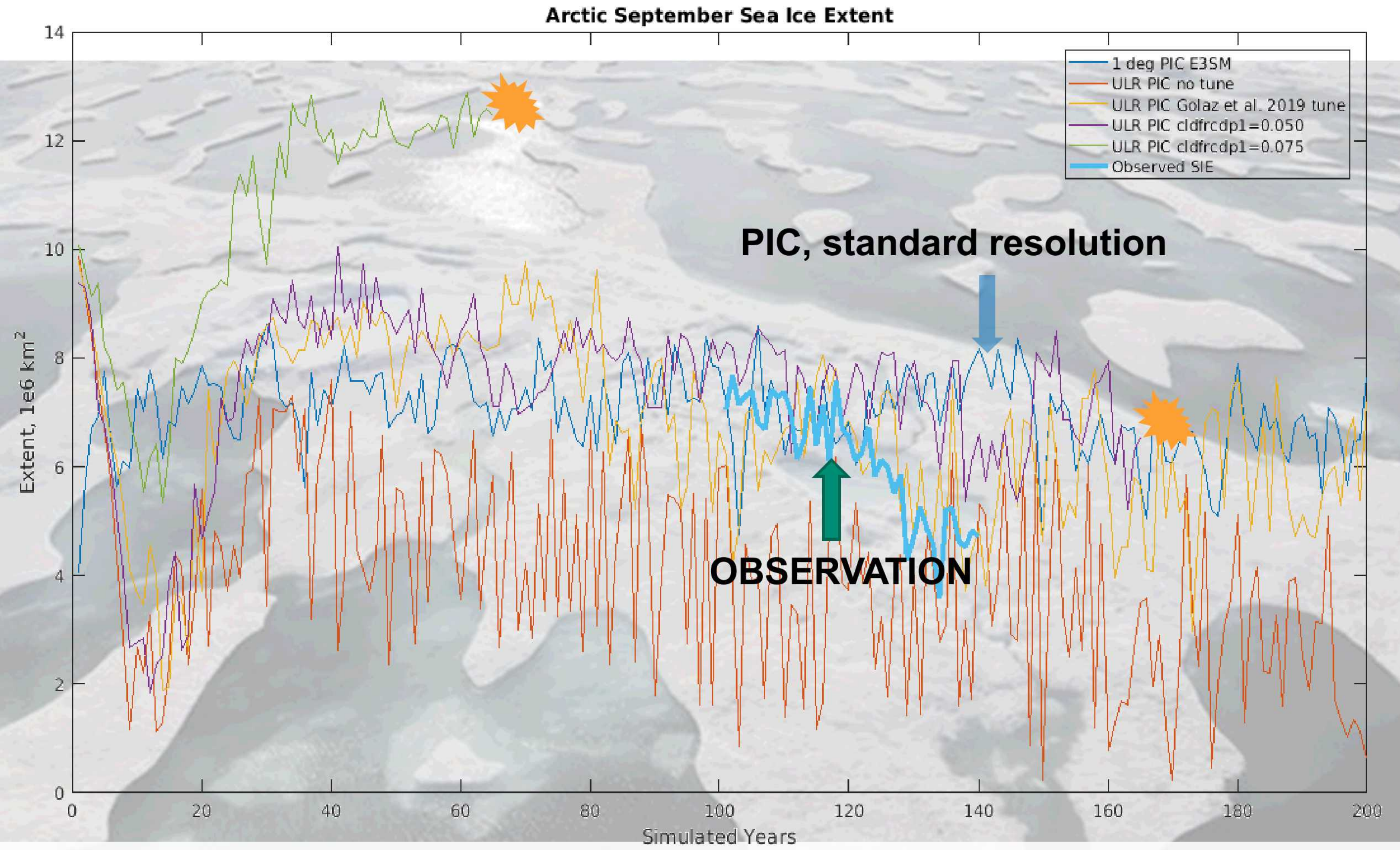
- **This QoI in all of our differently tuned E3SM ULR runs was significantly higher than the scientifically validated mean (E3SM 1- degree resolution)**
- **QoI is sensitive to deep convective cloud parameter cldfrc_dp1**

ULR (NE4) SIMULATIONS – Arctic Yearly Sea Ice Extent QoI with Different Tunings



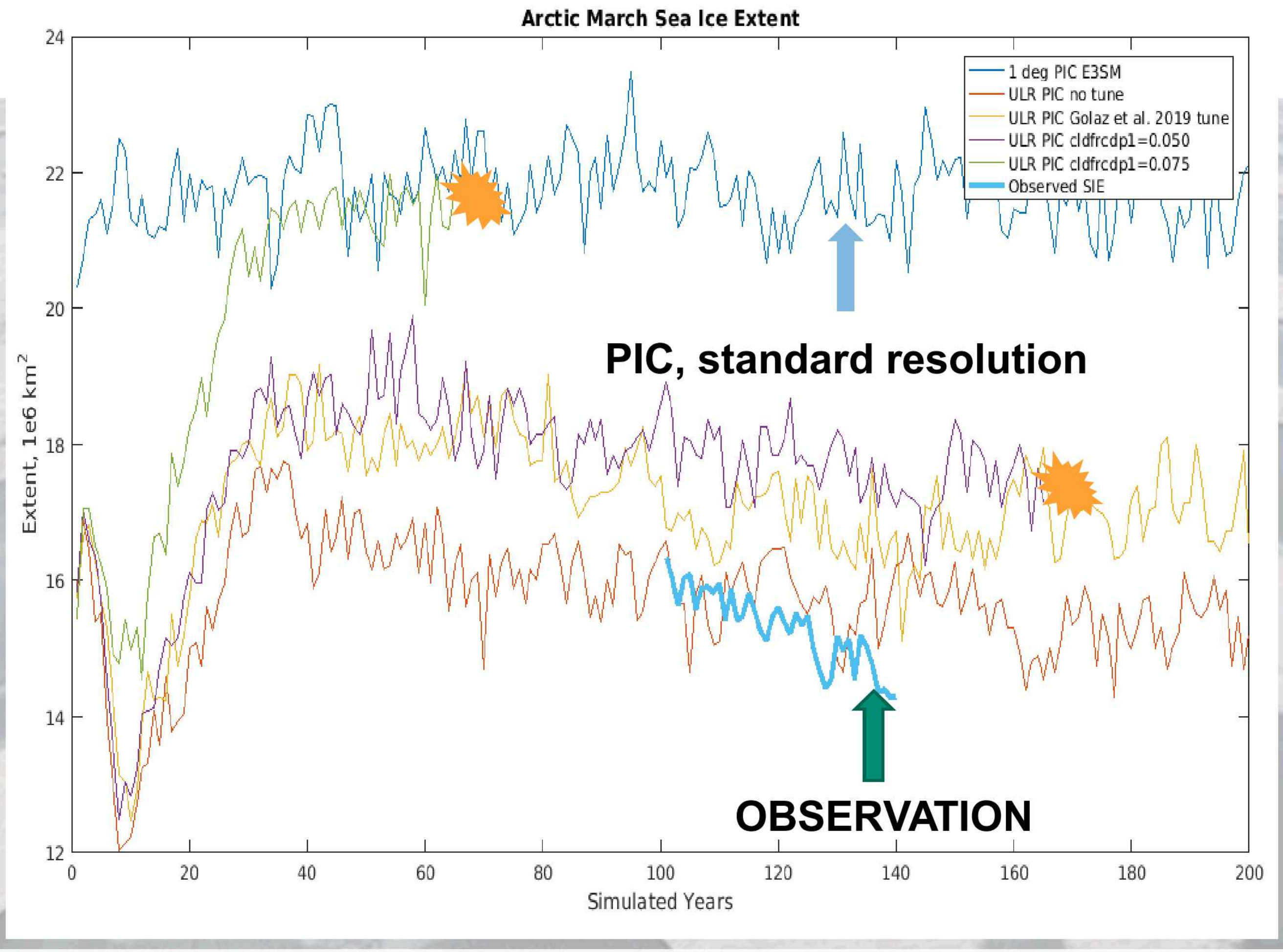
- **All tunings performed poorly, relative to observation and scientifically-validated standard simulation**
- **Golaz + cldfrc_dp1 = 0.05 tuning (purple) shows similar variation (shape and magnitude) to scientifically-validated simulation**

ULR (NE4) SIMULATIONS – Arctic September Sea Ice Extent QoI with Different Tunings



- Annual historical MINIMUM sea ice extent is in September
- Most tunings performed poorly (including and scientifically-validated simulation), relative to observation
- “Golaz et al. 2019” tuning (orange) tracks with September observations after year 100

ULR (NE4) SIMULATIONS – Arctic March Sea Ice Extent QoI with Different Tunings



- Annual historical MAXIMUM sea ice extent is in March
- Scientifically-validated standard resolution simulation models SIE observation poorly
- E3SM without tuning (red) approximates March SIE observations after year 100

ULR (NE11) SIMULATIONS – TBD QoI with Different Tunings

PLACE HOLDER

CONCLUSIONS

- **E3SM ULR simulations (with and without EAM tuning) are useful for studying aspects of Arctic climate and sea ice evolution**
  - **Radiative energy balance (shown in top of atmosphere net flux plot) at ne4 resolution (little to no tuning)**
  - **Sea ice maxima (March) at ne4 (no tuning)**
  - **Annual Sea Ice evolution at ne4 ("Golaz et al. 2019" + cldfrc_dp1 = 0.05 tuning)**

- **Tuning atmospheric parameters shows clear effects on key QoI**
  - **Global annual mean surface temperature**
  - **Annual mean sea ice extent**
  - **September sea ice extent (minimum)**
  - **March sea ice extent (maximum)**

- **Certain tunings are less discrepant with observation than the scientifically-validated, standard resolution PIC reference data**
  - **Sea ice maxima (March) at ne4 (no tuning and "Golaz et al. 2019 + cldfrc_dp1 = 0.050)**

- **Further exploration of key atmosphere tuning parameters could be valuable for making models consistent with climate reality**

NEXT STEPS

- **Support parameter sensitivity studies for sea ice (Tezaur *et al.*, in preparation)**

- **Scaling study for ne11 simulations (with 96, 192, 288, 480 processors on Skybridge)**

- **Continue tuning ne11 PIC model to approximate climate reality**

- **Analyze key QoI for 200-year simulations with the the deep convective cloud fraction tuning parameter (cldfrc_dp1) adjusted to values between 0.05 and 0.075**

- **Identify additionally potentially useful tuning parameters from other E3SM components (mpas-cice, mpas-ocean, ELM)**

ACKNOWLEDGEMENTS

- **ESCO Computational Methodologies for Next-Generation Climate Models Organizers**

- **Team Arctic Tipping Points: *Principal Investigator:* Kara Peterson; *Project Manager*: Mike Parks; Diana Bull, Warren Davis, Jake Nichol, Matt Peterson, Erika Roesler, David Stracuzzi, Irina Tezaur, Ray Bambha, Jennifer Frederick, Jasper Hardesty, Anastasia Ilgen, John Jakeman, Cosmin Safta**

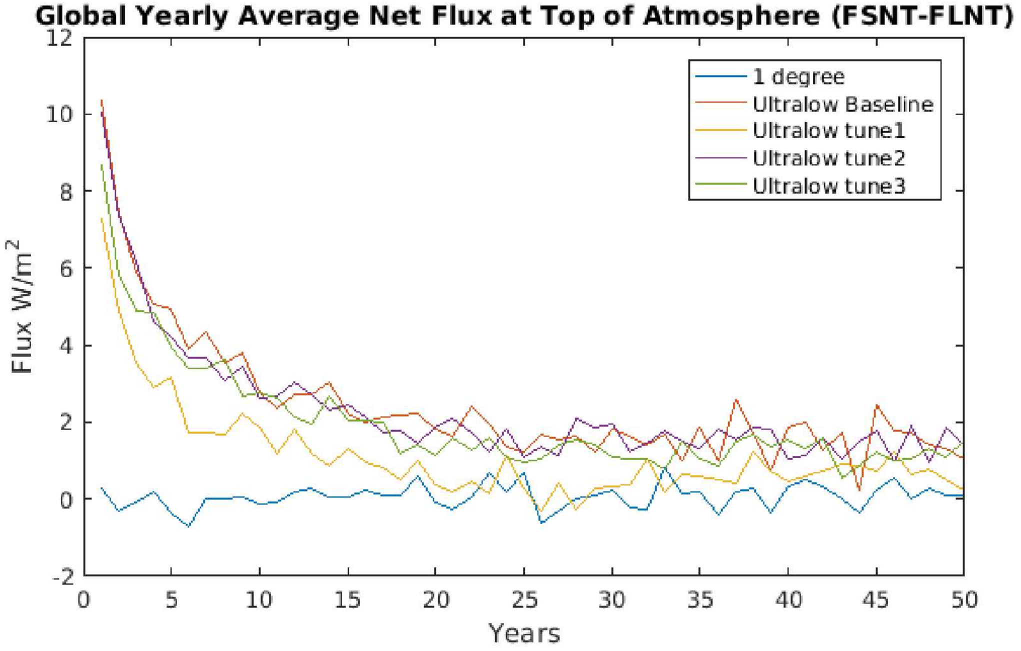
- **Sandia National Laboratories LDRD Office ("Artic Tipping Points Triggering Global Change," Project 209230)**

- **Sandia High Performance Computing**

BACKUPS

TECHNICAL PROGRESS SUMMARY– COUPLED MODELING

- **Accomplishments**
  - Completed 500-year pre-industrial control baseline simulation on Skybridge
  - 5 additional simulations completed with different values for resolution-dependent atmospheric variables
  - Developed scripts/framework for comparisons with E3SM 1-degree CMIP6 data and observational data
  - Analysis of E3SM 1-degree simulation results for sea ice trends and internal variability ongoing
- **Significance**
  - Tuned fully-coupled low-resolution model
    - Enables capability to quickly evaluate the relative effects of changing parameters
    - Ideal for use in sensitivity and stability studies
  - Analysis of sea ice response in coupled dynamical system will provide insights into key drivers and feedbacks. Are teleconnections more important than local changes?



- **Next Steps**
  - Sensitivity study of Arctic sea ice response to perturbations in sea ice/ocean/atmosphere parameters
  - Investigate important feedbacks and sensitivities using information from data model feature importance measures

PROJECT RESULTS

- **Peer-Reviewed Publications**
  - Planned and In Progress
    - Matt Peterson, Jake Nichol, et al. “Predicting Arctic sea ice concentration with data-driven models”, *The Cryosphere*, in preparation for submission FY20.
    - Erika Roesler, Amy Powell, et al. “Ultra-low resolution E3SM coupled simulations for stability analysis”, *JAMES*, in preparation for submission FY20.
    - Kara Peterson, Irina Tezaur, et al. “Sensitivity analysis of Arctic sea ice in a coupled Earth system model”, Climate Dynamics, in preparation for submission FY20.
- **Other Publications**
    - Kara Peterson, Matt Peterson et al. “2020 Sea Ice minimum extent prediction from data-driven model”, 2020 Sea Ice Outlook Report, in preparation for submission July/August 2020.
- **Presentations: Workshops, Conferences, Industry Days**
  - Minisymposium Organization
    - I. Tezaur, M. Perego, J. Frederick, K. Peterson “New Developments in Computational Modeling of Cryosphere Systems” for International Congress on Industrial and Applied Mathematics (ICIAM), Valencia, Spain, July 2019.
  - Workshops
    - Applied Math Visioning Workshop on the Future of Machine Learning and Data Analytics Across the Department of Energy, LBNL, March 2019. M. Peterson (invited participant) and K. Peterson (co-organizer).

PROJECT RESULTS

- **Presentations: Workshops, Conferences, Industry Days**
  - Presentations
    - M. Peterson, “Predicting Arctic sea ice concentration with data-driven models”, ICIAM, Valencia, Spain, July 2019.
    - K. Peterson, “Sea Ice Modeling and Arctic Change”, UNM Women in Computing Seminar, March 2019.
    - D. Bull, “National security implications from tipping events centered in Arctic waters”, 2018 International Symposium: Climate Change Effects on the World’s Oceans, 4-8 June 2018, Washington DC.
    - D. Bull, “Methodologies to Optimize Changing National Security Preparedness Demands Arising with Increasing Arctic Access”, DoD Arctic S&T Synchronization Workshop, 16-18 May 2018, CRREL.
  - Posters
    - M. Peterson, “Predicting Minimum Arctic Sea Ice Extent”, Sandia Machine Learning R&D Workshop, September 2019
    - J. Nichol, “Using Machine Learning to Compare Simulated and Observational Sea Ice Extent Data”, AGU Fall Meeting, December 2019
    - K. Peterson, “Arctic Sea Ice Internal Variability in E3SM and Its Response to Anthropogenic Forcing”, AGU Fall Meeting, December 2019.
    - A. Powell, “Exploring the Use of Ultra-Low Resolution E3SM Simulations to Predict Sea Ice – Free Summers, and to Elucidate the Role of Arctic Sea Ice in Polar Amplification”, AGU Fall Meeting, December 2019

PROJECT RESULTS

Project Briefings with Arctic Stakeholders at SNL

- Elizabeth Moore, October 7, 2019
- DOE International Affairs and USAF Visitors, August 7, 2019
- Fran Ulmer, Chair, US Arctic Research Consortium, USARC, May 23-24, 2019
- Martin Jeffries, Senior Leadership, Army Cold Regions Research and Engineering Lab, USACE-CRREL, April 17, 2019
- Sally McFarlane, DOE Office of Science ARM program leader, January 7, 2019
- Jim Mather, PNNL, technical director for ARM, January 7 2019
- Hal Moore, Chief Technology Officer, NORAD-NORTHCOM, June 28, 2018
- Mekisha Marshall, Chief Science and Technology Advisor, NMIO, June 28, 2018
- Nicki Hickmon ANL, infrastructure director for ARM, January 7, 2019 and February 15, 2018
- Peter Davies, Global Fellow, Wilson Center, February 18, 2018
- Sheri Goodman, Senior Fellow, Wilson Center, April 11, 2018
- Mike Sfraga, Director, Polar Initiative, Wilson Center, April 11, 2018

TEAM BUILDING AND PARTNERSHIPS

- **Career Development**
  - Matt Peterson, early career
  - Jake Nichol, UNM, year-round intern

- **External Partnerships**
  - Looking into making connections with the recently funded MURI project "Mathematics and Data Science for Improved Physical Modeling and Prediction of Arctic Sea Ice", NYU Courant, Dimitris Giannakis, Georg Stadler
  - Submitted Academic Alliance proposal in partnership with Patrick Heimbach director of Computational Research in Ice and Ocean Systems Group at UT Austin for FY20.

- **Internal Partnerships**
  - Warren Davis (1461) has joined the LDRD this FY and we are investigating synergies with his ASCR project focusing on anomaly detection.

CAPABILITIES DEVELOPMENT

- **<u>Establishment of Capabilities expected to impact future work</u>**
  - Developed new data-driven model for seasonal sea ice extent forecasting with relevance for the Navy and other Arctic stakeholders.
  - Developing tuned ultra-low resolution E3SM configuration for use in quickly evaluating parameters and gaining insight into feedbacks and sensitivity of global coupled model.
  - SNL staff gaining expertise in running coupled E3SM code on HPC platforms, important for future connections with BER.
  - Deepening understanding of Earth system components and their interactions in the Arctic.