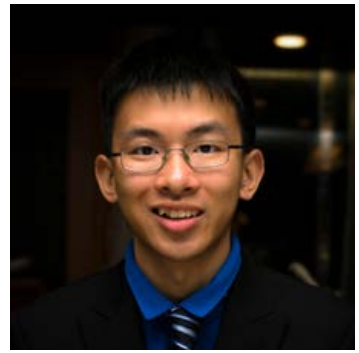
The response of tropical cyclone activity to increasing CO2 in the Community Earth System Model

Ryan Sriver, University of Illinois, Dept. of Atmospheric Sciences

Student/Postdoc Collaborators:

Hui Li, Yale University
Andrew Huang, Naval Research Laboratory
Ben Vega Westhoff, University of Illinois


NCSA Collaborators:

David Bock, Lead Visualization Programmer
Ryan Mokos, Senior Research Programmer
Rob Sisneros, Data Analytics and Visualization Group

Ongoing work supported by:

Blue Waters Symposium, Sunriver, Oregon, June 4, 2019

Tropical cyclones (e.g. hurricanes) pose serious risks

Katrina, 2005

Harvey, 2017

Tied for costliest hurricanes on record
$125 Billion each (2017 USD)

Photo: PBS/NOAA

Photo: Wikipedia Commons

Understanding connections between tropical cyclones and climate is critical for coastal planning and flood risk assessments

How will TCs change in the future?

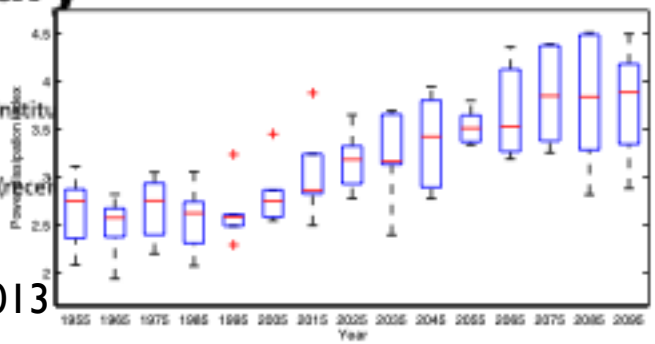
PNAS

Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century

Kerry A. Emanuel[1]

Program in Atmospheres, Oceans, and Climate, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institu
Cambridge, MA 02139

Edited by Benjamin D. Santer, E. O. Lawrence Livermore National Laboratory, Livermore, CA, and approved June 10, 2013 (recei
January 20, 2013)



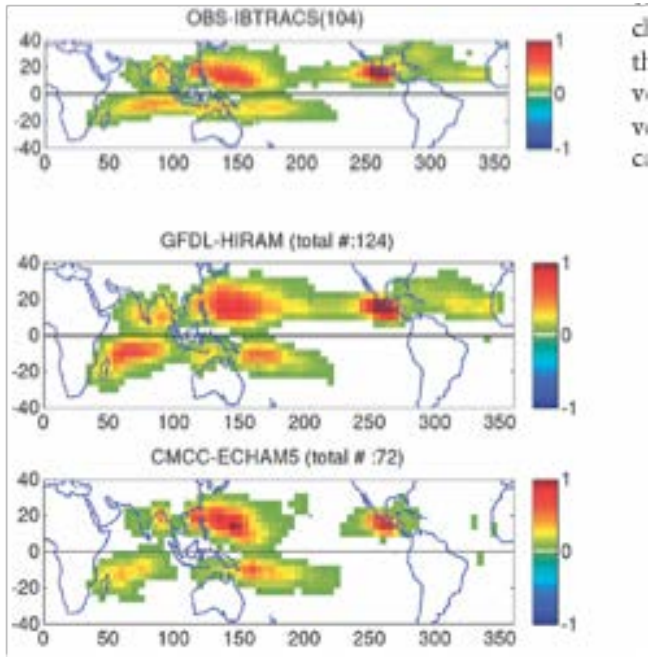
Emanuel, 2013

HURRICANES AND CLIMATE

The U.S. CLIVAR Working Group on Hurricanes

BY KEVIN J. E. WALSH, SUZANA J. CAMARGO, GABRIEL A. VECCHI, ANNE SOPHIE DALOZ, JAMES ELSNER, KERRY EMANUEL, MICHAEL HORN, YOUNG-KWON LIM, MALCOLM ROBERTS, CHRISTINA PATRICOLA, ENRICO SCOCCIMARRO, ADAM H. SOBEL, SARAH STRAZZO, GABRIELE VILLARINI, MICHAEL WEHNER, MING ZHAO, JAMES P. KOSSIN, TIM LAROW, KAZUYOSHI OUCHI, SIEGFRIED SCHUBERT, HUI WANG, JULIO BACMEISTER, PING CHANG, FABRICE CHAUVIN, CHRISTIANE JABLONOWSKI, ARUN KUMAR, HIROYUKI MURAKAMI, TOMOAKI OSE, KEVIN A. REED, RAMALINGAM SARAVANAN, YOHEI YAMADA, COLIN M. ZARZYCKI, PIER LUIGI VIDALE, JEFFREY A. JONAS, AND NAOMI HENDERSON

Although a theory of the climatology of tropical cyclone formation remains elusive, high-resolution climate models can now simulate many aspects of tropical cyclone climate.



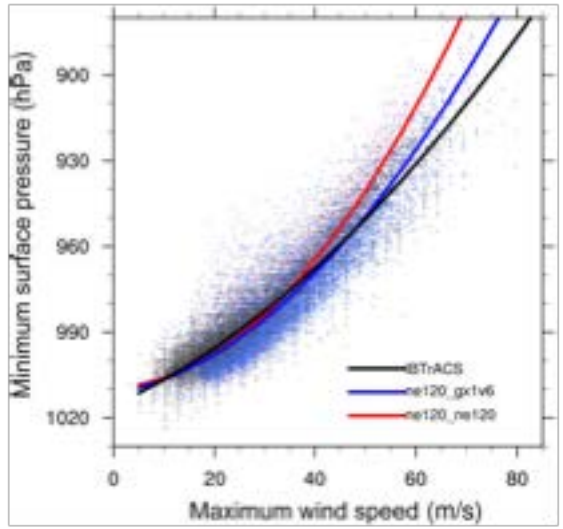
Walsh et al., 2015

The question is difficult to answer with global models due to coarse resolution and lack of ocean-atmosphere coupling

What has been done with CESM?

Geosci. Model Dev., 9, 779–788, 2016
www.geosci-model-dev.net/9/779/2016/
doi:10.5194/gmd-9-779-2016

Geoscientific Model Development
Open Access
EGU



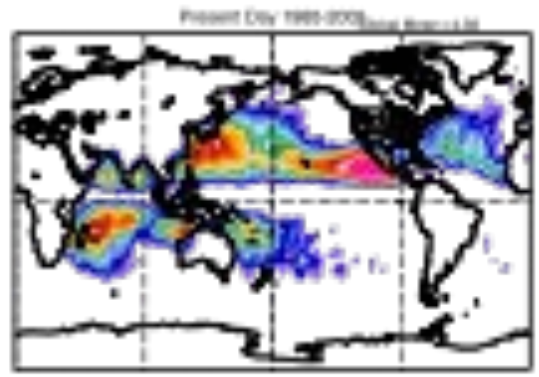
Impact of surface coupling grids on tropical cyclone extremes in high-resolution atmospheric simulations

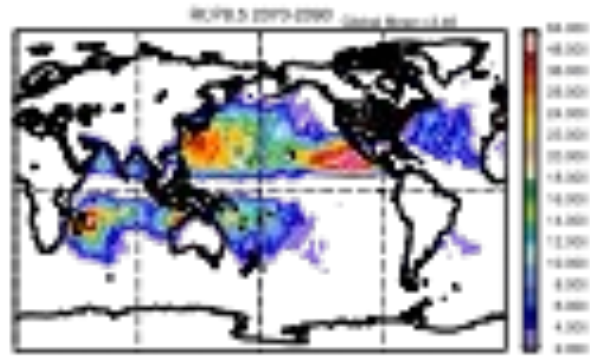
Colin M. Zarzycki[1], Kevin A. Reed[2], Julio T. Bacmeister[1], Anthony P. Craig[1], Susan C. Bates[1], and Nan A. Rosenbloom[1]

[1]National Center for Atmospheric Research, Boulder, Colorado, USA
[2]School of Marine and Atmospheric Sciences, State University of New York at Stony Brook, Stony Brook, New York, USA

Climatic Change
DOI 10.1007/s10584-016-1750-x

CrossMark





Projected changes in tropical cyclone activity under future warming scenarios using a high-resolution climate model

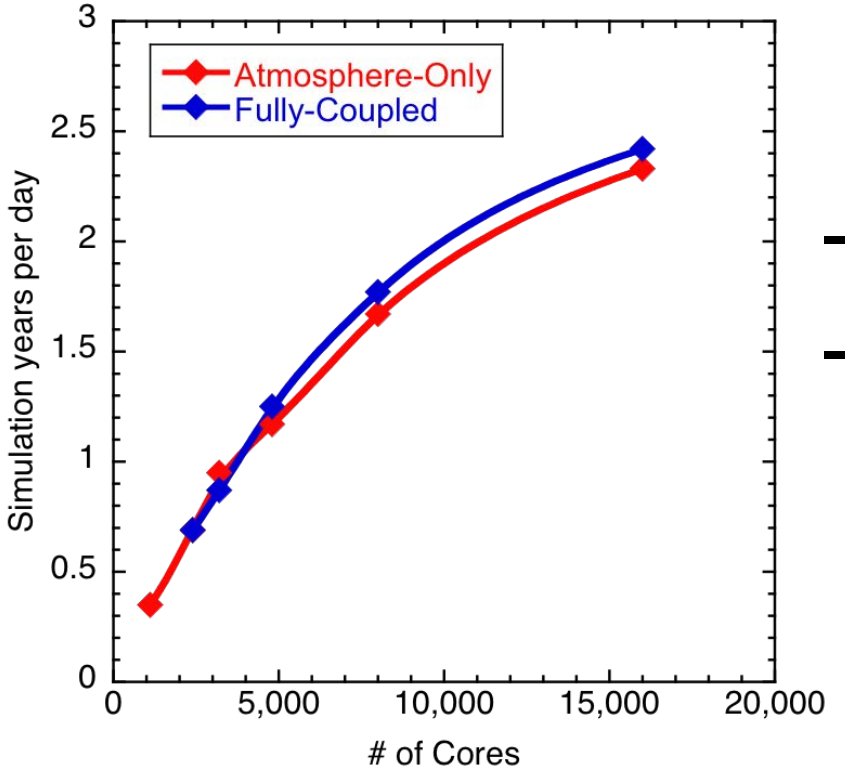
Julio T. Bacmeister[1] · Kevin A. Reed[2] · Cecile Hannay[1] · Peter Lawrence[1] · Susan Bates[1] · John E. Truesdale[1] · Nan Rosenbloom[1] · Michael Levy[1]

Received: 12 November 2015 / Accepted: 12 July 2016

Our approach to the TC-Climate problem:

Hierarchical experiment using high-resolution configurations of CESM to analyze TC-climate relationship

Why Blue Waters?

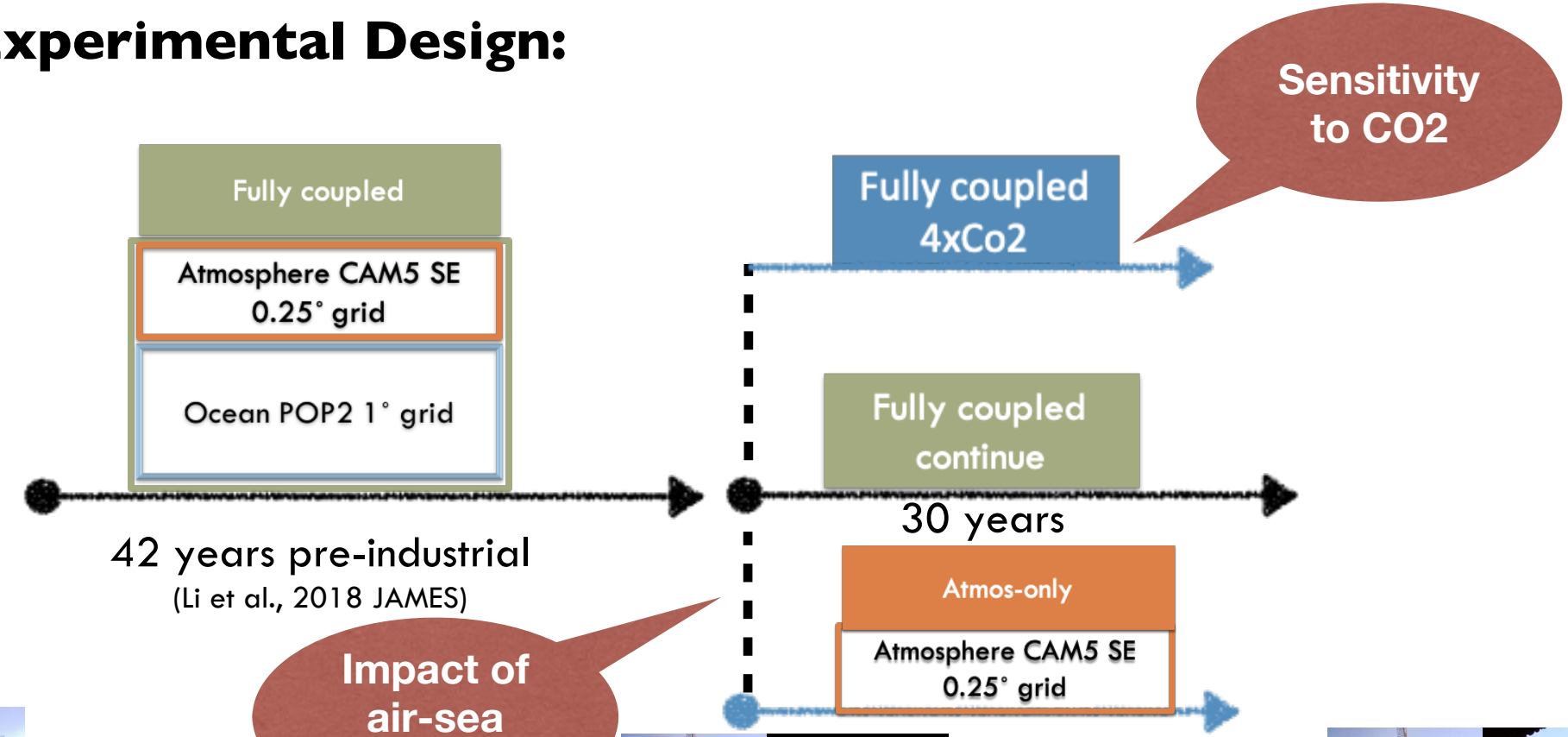


- Model version adapted from other groups — Susan Bates (NCAR) and Don Wuebbles (UIUC)
- CESM scales well on Blue Waters to ~15,000 cores
  - Extensive load balancing (Hui Li) to optimize cost

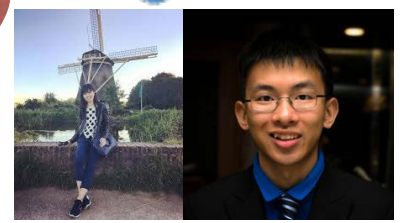
Major Challenge: Analyzing weather in a climate model

- Fine spatial resolution (0.25 deg atm, ~1 deg ocean)
- Coupling ocean and atmosphere (scale mismatch)
- Integration length (multi-decadal simulations)
- High frequency IO (sub daily model outputs)
- Post-processing (analyzing and visualizing the results)

Experimental Design:



2015



2017

2019

Total Cost:

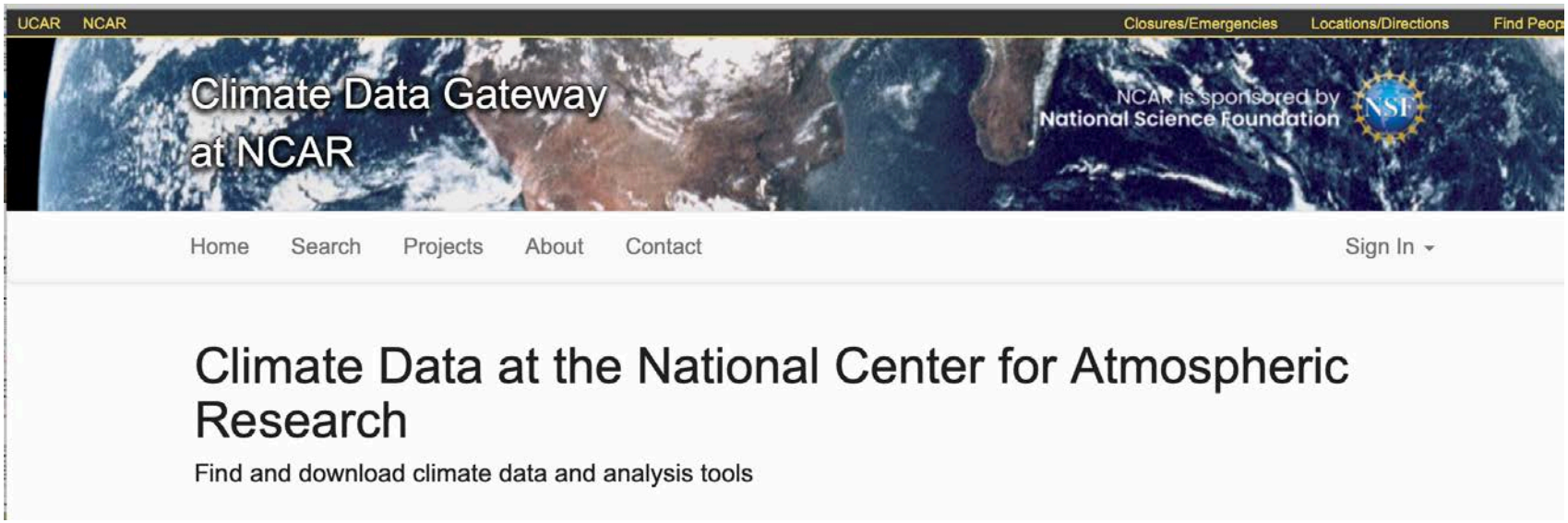
- 40 million core hours (with extensive load balancing)

Total Size:

- 100 TB (includes monthly daily, and sub daily fields)

Data is available on NCAR's Climate Data Gateway:

https://www.earthsystemgrid.org



Example: Search term — TC

Download Selected

CCSM run TC-CESM.atm_only_newcompset, Atmosphere Post Processed Data, 6-Hourly Averages, version 1

CCSM run TC-CESM.atm_only_newcompset, Atmosphere Post Processed Data, Daily Averages, version 1

CCSM run TC-CESM.atm_only_newcompset, Atmosphere Post Processed Data, Monthly Averages, version 1

6-hourly variables

T300	Temperature at 300 mbar pressure surface	K
T500	Temperature at 500 mbar pressure surface	K
TBOT	Lowest model level temperature	K
U10	10m wind speed	m/s
U850	Zonal wind at 850 mbar pressure surface	m/s
UBOT	Lowest model level zonal wind	m/s
V850	Meridional wind at 850 mbar pressure surface	m/s
VBOT	Lowest model level meridional wind	m/s

Special thanks to Susan Bates and Gary Strand at NCAR

Some recent highlights and products:

TC Impacts on the Ocean

- Li, H. and Sriver, R. L. (2016), Effects of ocean grid resolution on tropical cyclone-induced upper ocean responses using a global ocean general circulation model, Journal of Geophysical Research-Oceans, 121, 8305-8319, doi:10.1002/2016JC011951.
- Li, H., Sriver, R. L., and Goes, M. (2016), Modeled sensitivity of the Northwestern Pacific upper-ocean response to tropical cyclones in a fully-coupled climate model with varying ocean grid resolution, Journal of Geophysical Research-Oceans, 121, doi:10.1002/2015JC011226.
- Li, H. and Sriver, R. L. (2018), Impact of tropical cyclones on the global ocean: Results from multi-decadal global ocean simulations isolating tropical cyclone forcing, Journal of Climate, 31, 8761-8784, doi:10.1175/JCLI-D-18-0221.1.

TCs in Coupled vs Atmosphere-Only Simulations

- Huang, A., Li, H., Sriver, R. L., Fedorov, A. V., and Brierley, C. M. (2017), Regional variations in the ocean response to tropical cyclones: Ocean mixing versus low cloud suppression, Geophysical Research Letters, doi:10.1002/2016GL072023.
- Li, H. and Sriver, R. L. (2018), Tropical cyclone activity in the high-resolution Community Earth System Model and the impact of ocean coupling, Journal of Advances in Modeling Earth Systems, 10, doi:10.1002/1017ms001199.
- Li, H., and Sriver, R. L., (2019), Impact of air-sea coupling on the simulated global tropical cyclone activity in the high-resolution Community Earth System Model (CESM), Climate Dynamics, doi:10.1007/s00382-019-04739-8.

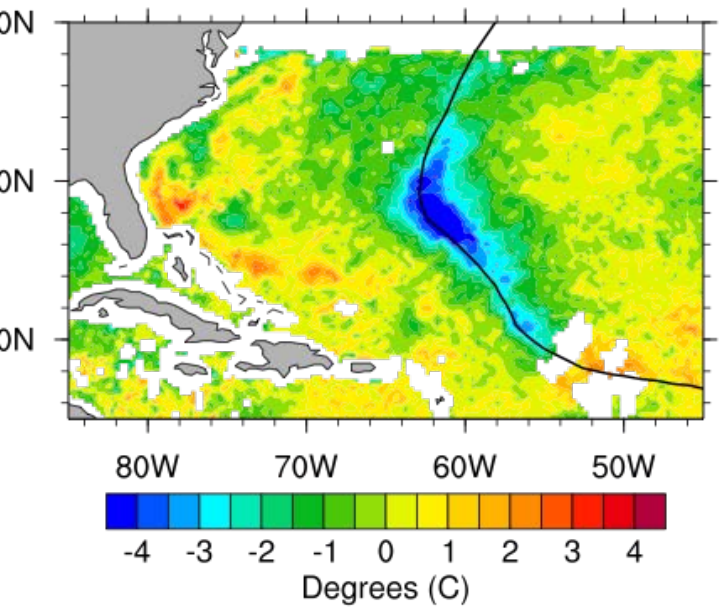
Response in TC activity to CO2

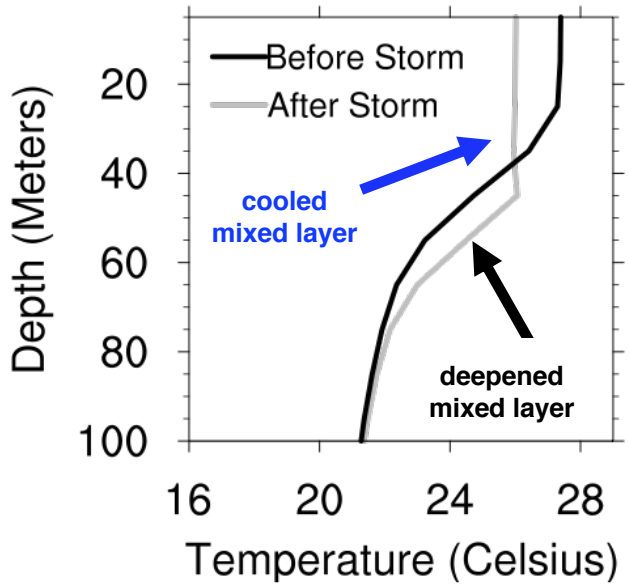
- Work in Progress

Impact of TCs on the Ocean

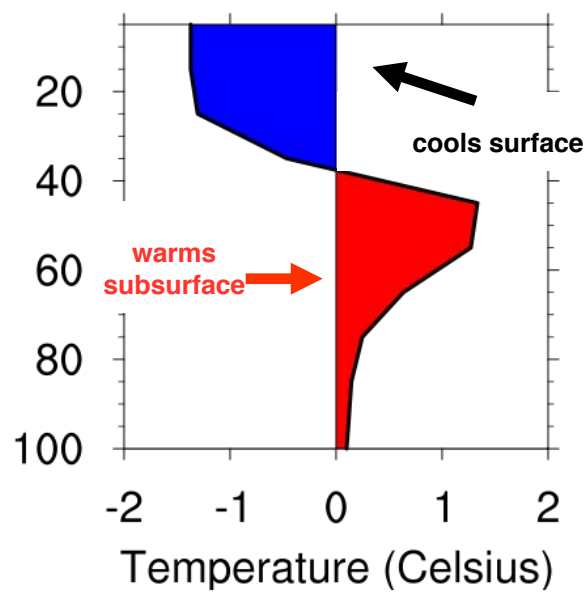
- Tropical cyclones tend to cool the surface ocean primarily by vertical ocean mixing
- TC-induced mixing redistributes heat vertically in ocean column leading to subsurface warming

Hurricane Gert, 1999





post-storm minus pre-storm



Sriver, 2013 — PNAS

What happens to the subsurface heat heat?
Does TC-mixing contribute to heat and energy budgets?
What is the effect on large-scale variability?

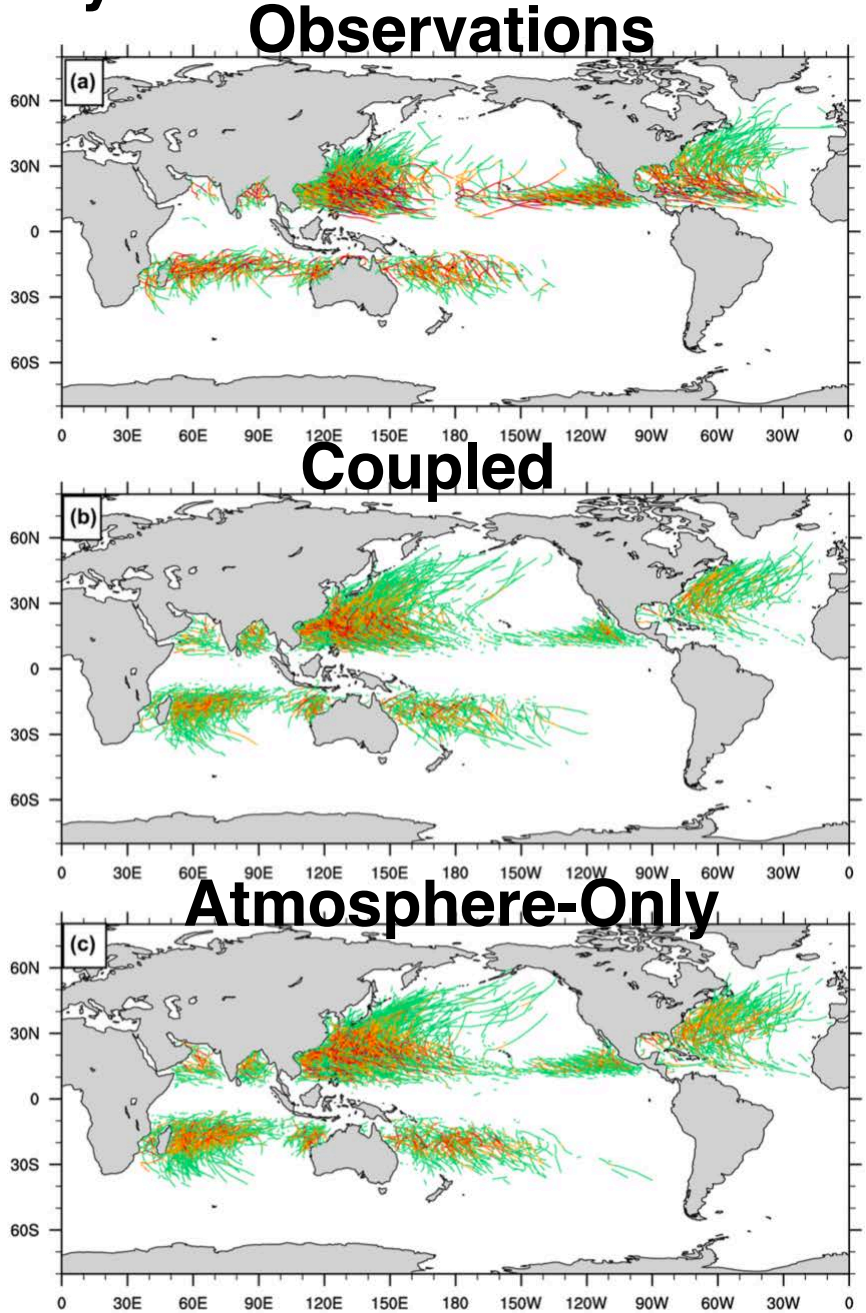
Animations for visualizing TC-ocean interactions in CESM using Blue Waters

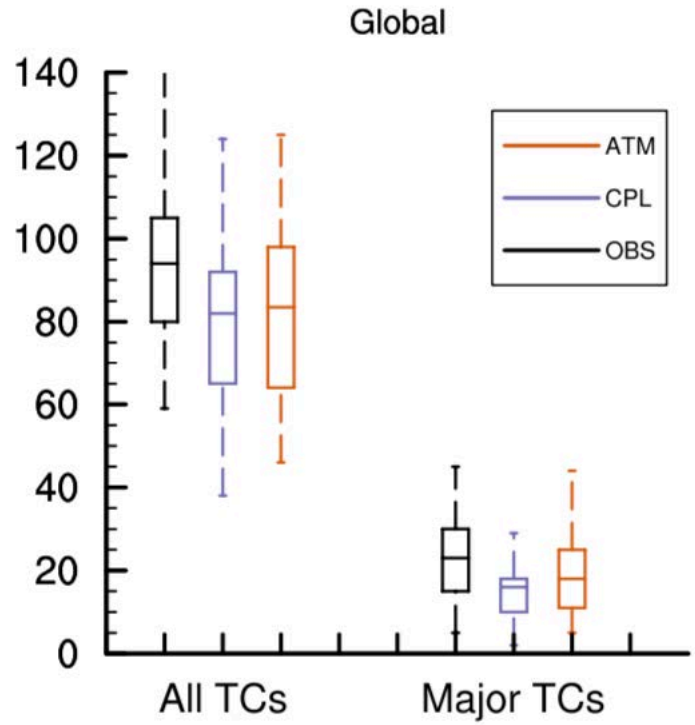
Produced by David Bock and Rob Sisneros
National Center for Supercomputing Applications (NCSA)
Data Analytics and Visualization

http://manabe.atmos.uiuc.edu/~rsriver/Bock_Climate_SC_revised.mp4

Li and Sriver, 2016 —JGR Oceans

TCs in coupled ocean-atmosphere and atmosphere-only simulations



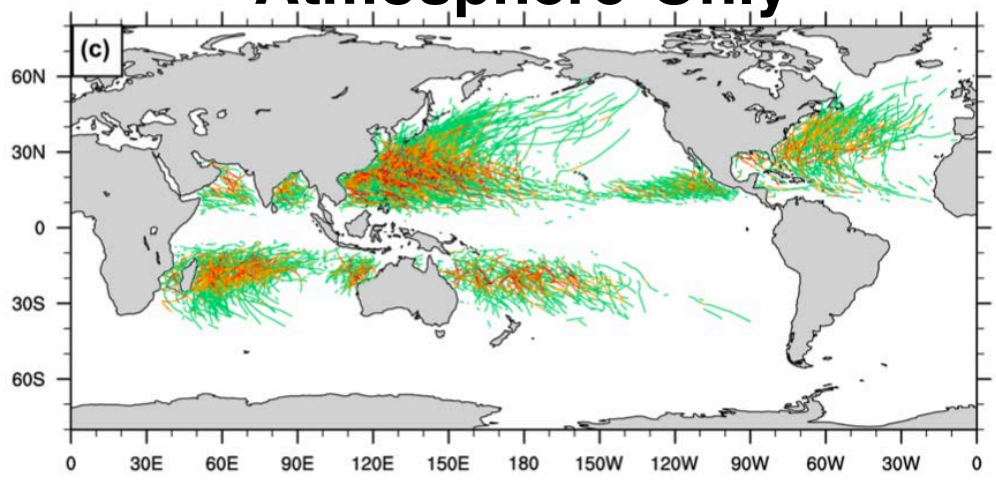


- CESM generally reproduces observed TC activity (locations, intensity, seasonality)
- More intense storms in atmosphere-only simulation (no ocean mixing!)

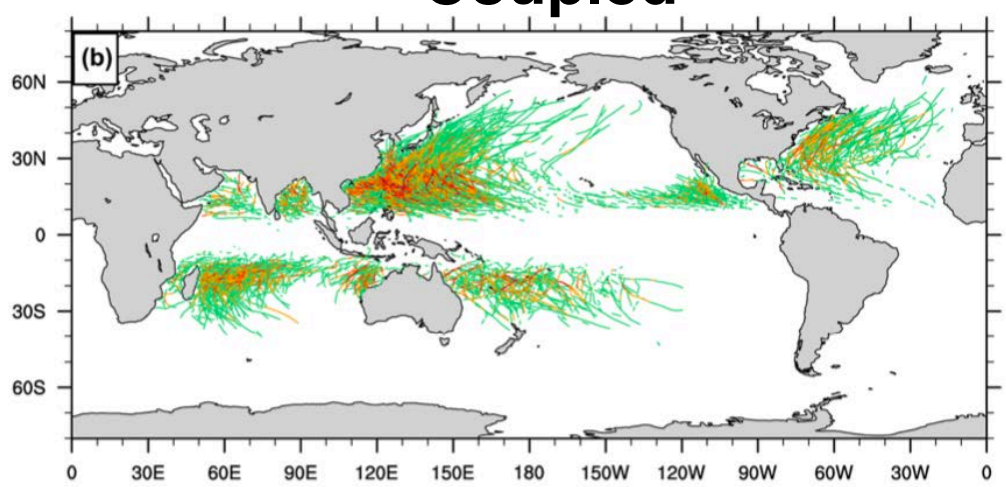
Li and Sriver, 2018; Li and Sriver, 2019

TCs in coupled ocean-atmosphere and atmosphere-only simulations

Atmosphere-Only

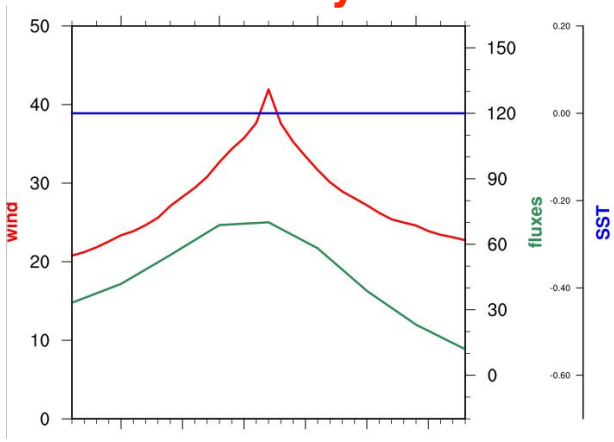


Coupled



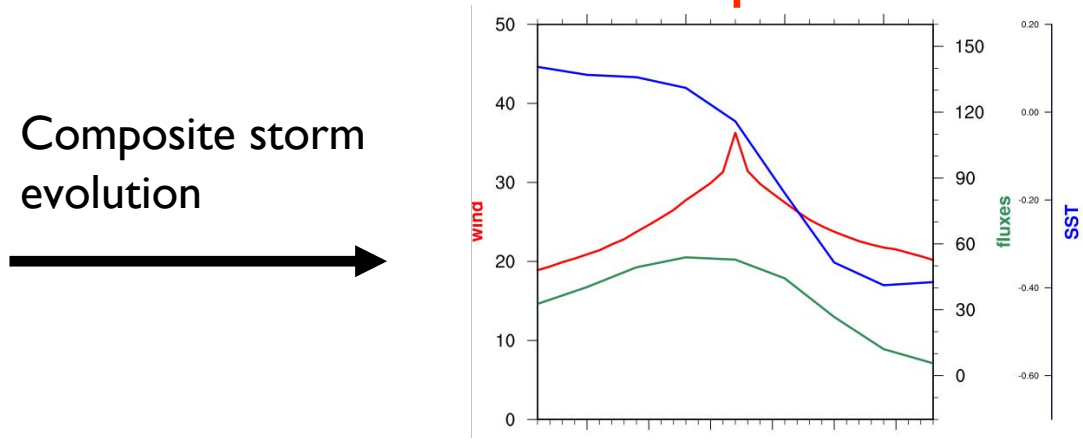
Atm-Only

SFC TEMP
SFC WIND
SFC FLUXES



Time

Composite storm evolution



Coupled

Time

- Coupled CESM simulates 27% less major TCs
  - Decreased power dissipation and equatorward shift in peak intensity

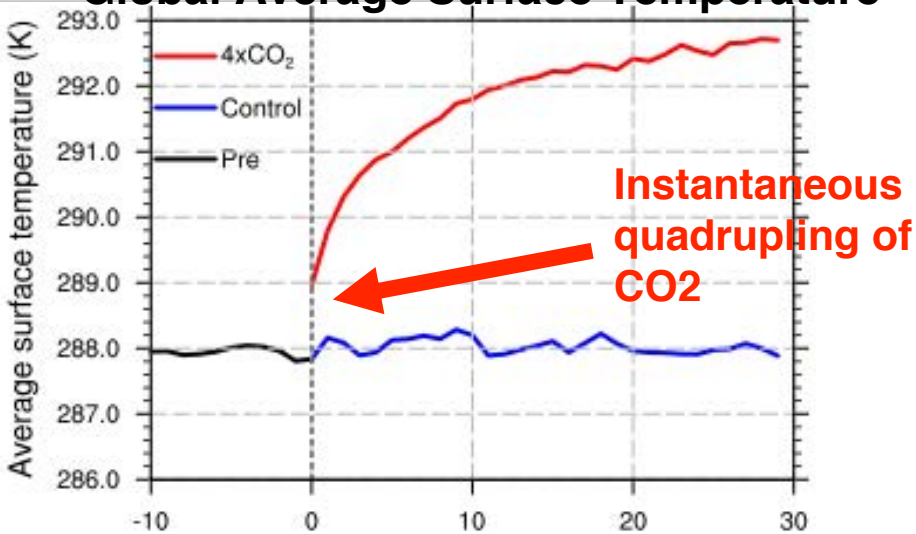
- Ocean-Atmosphere interactions can modulate TC intensity, evolution, activity and variability
  - Models with fixed ocean conditions are missing these feedbacks

Response in TC activity to increased CO2

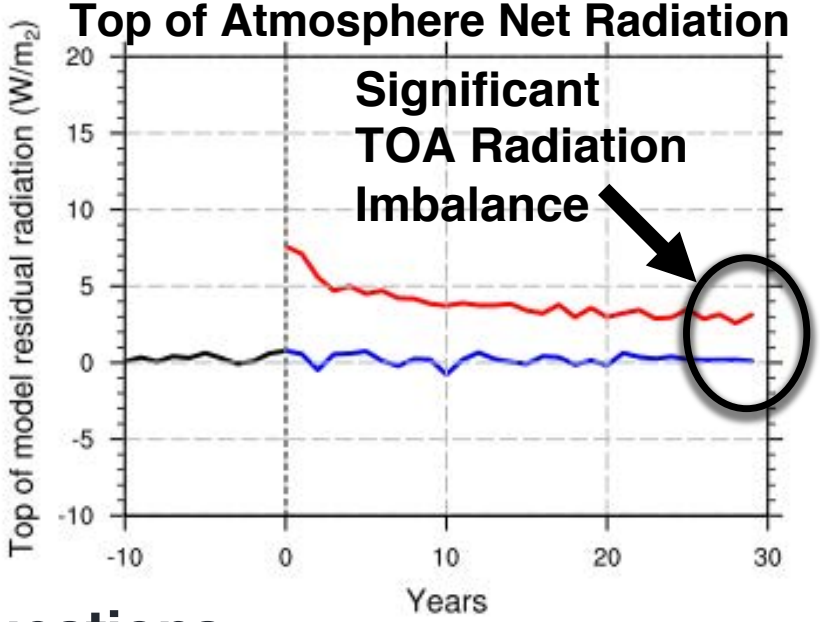
4xCO2 Simulation:

- Branched from coupled control
- Instantaneous quadrupling of atmospheric CO2
- 30-year simulation
- Compare TC stats and anomalies with control run

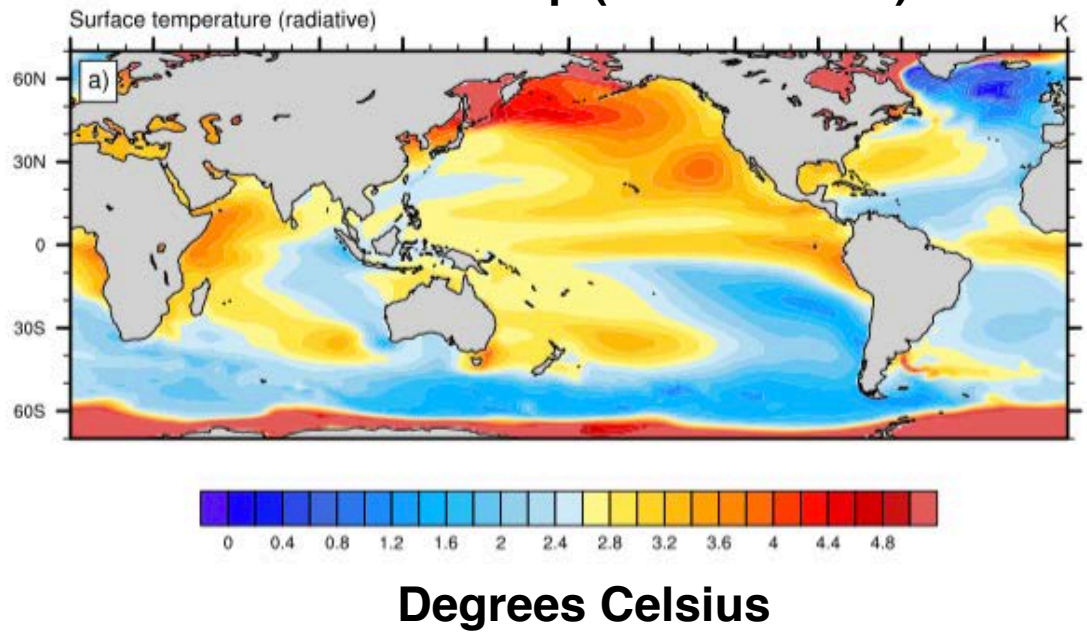
Global Average Surface Temperature



Top of Atmosphere Net Radiation



Surface Temp (4xCO2 - CTL)



Questions:

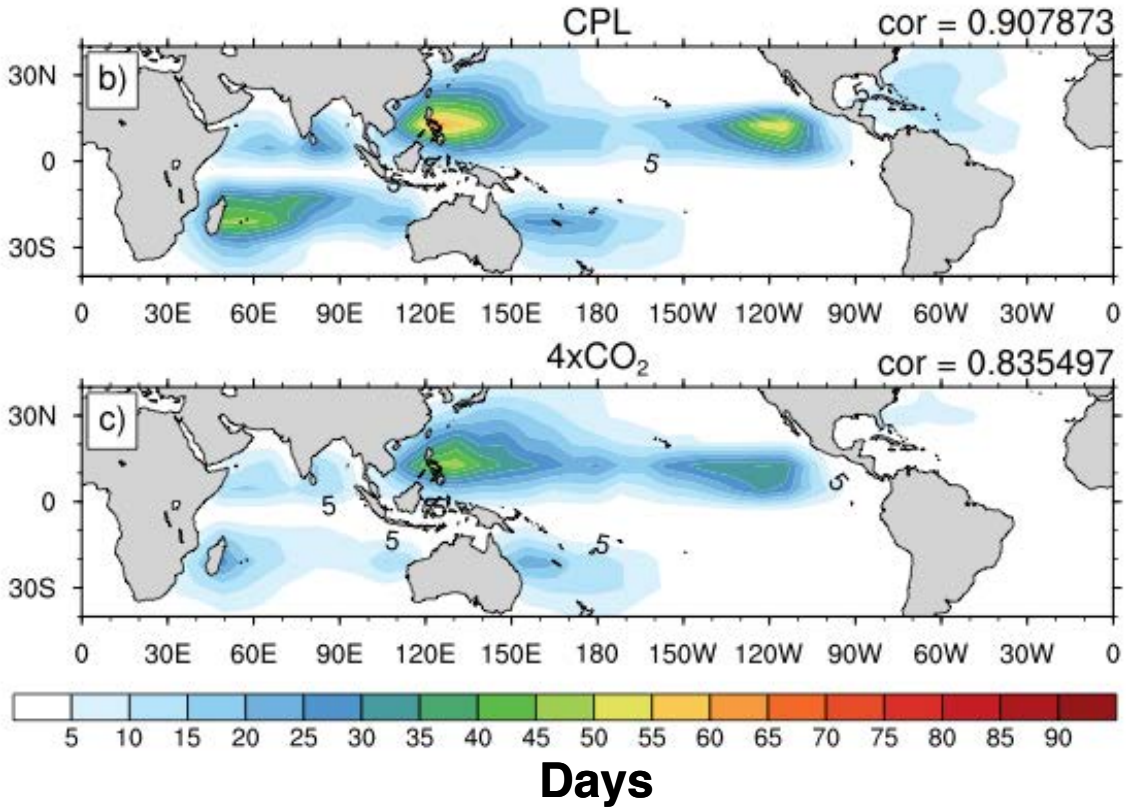
- How does TC activity change under extreme radiative forcing?
- Can we learn something about environmental factors controlling TC activity?

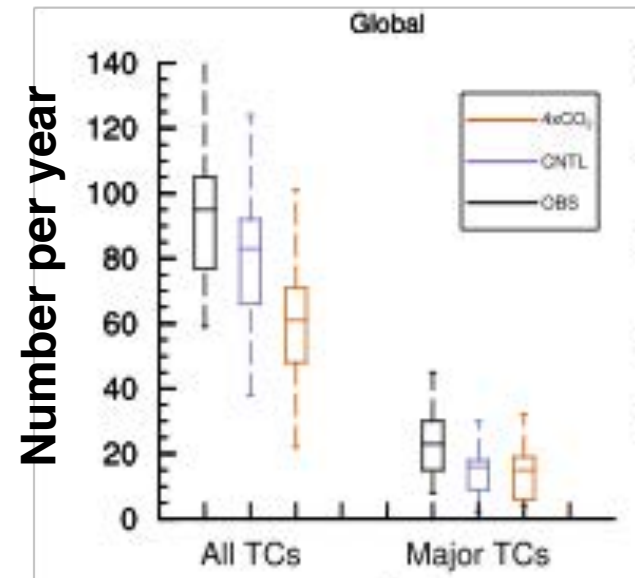
Response in TC activity to increased CO2

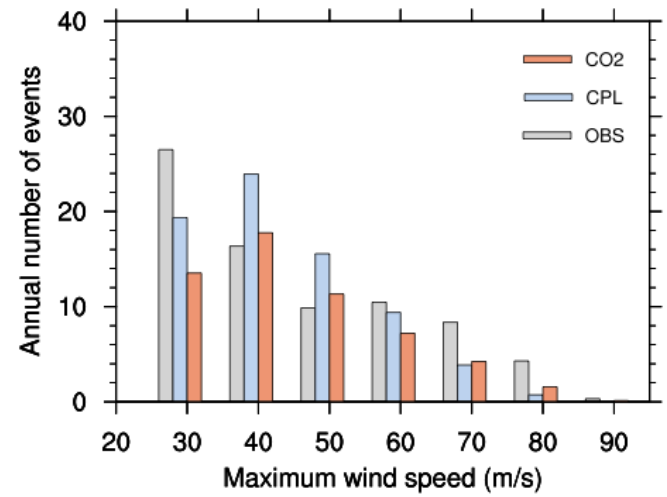
Storms per year

	4xCO2	Control
AT	4	8
EP	13	16
NWP	19	25
SH	15	30

TC Track Density







Under 4xCO2 conditions:

- Decrease in storm counts
- Increase in storm intensity

Why?

- Tradeoffs between enhanced vertical wind shear and increased SST

Ongoing Work:

- Compare/Contrast CESM results with downscaling methods (cf. Emanuel, 2013)
- Preliminary results indicate similar sensitivity to interactive ocean mixing
- Downscaling provides thousands more TC tracks, but lacks physical consistency in CESM

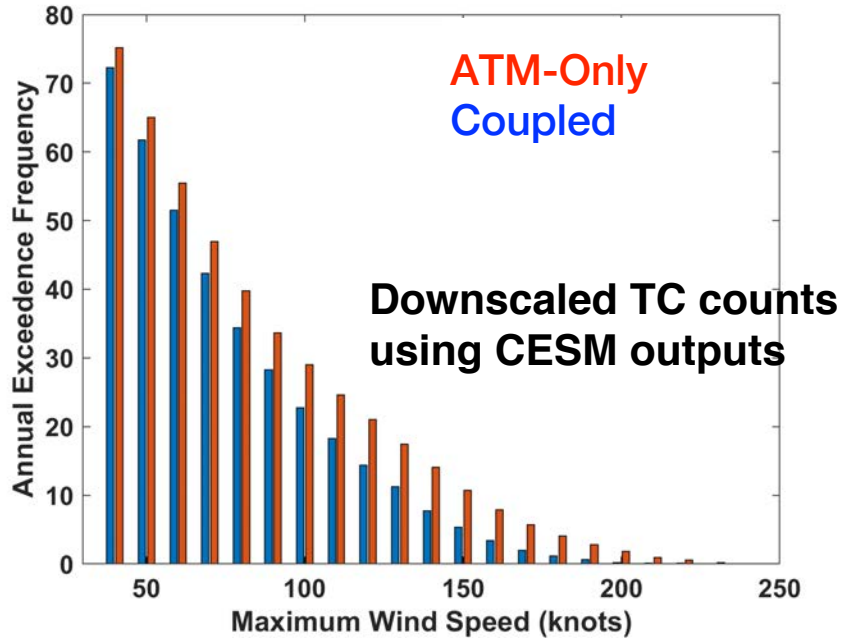
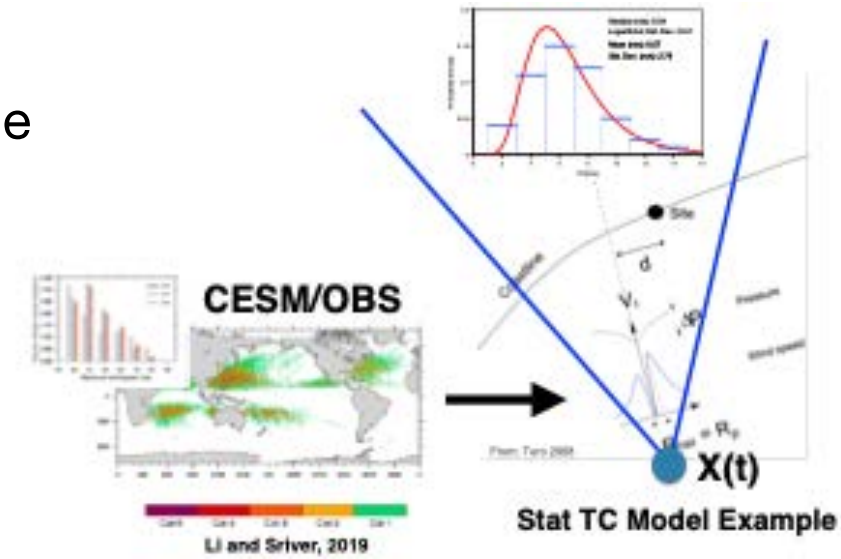


Figure Courtesy of K. Emanuel

Future Directions:

- Combine numerical/statistical models to examine factors influencing TC changes and variability
- Deep-learning could be very useful due to data size, multi-scale interactions, and non-linear relationships
- Probabilistic TC projections for coastal flood risk assessment



Some Conclusions:

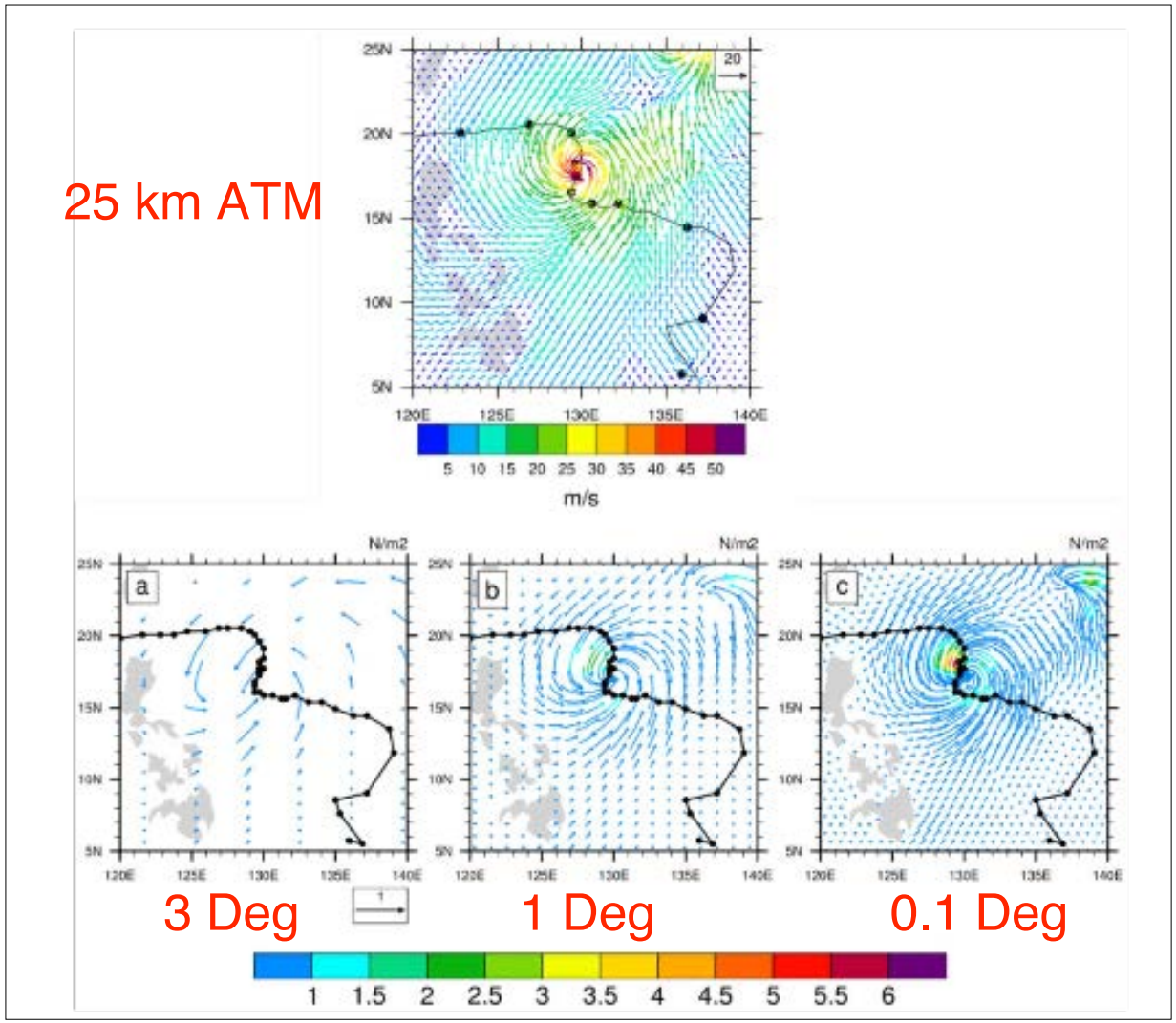
- **We conducted a series of multi-decadal CESM simulations examining the relationship between TC-climate interactions**

- **Ocean-Atmosphere coupling significantly influences TC activity and the feedbacks could be important for large-scale ocean and atmosphere energy budgets and circulations.**

- **Increasing CO2 leads to reduction in overall number of storms while increasing intensity of most intense storms**

Extra Slides

TC structure in high-res CESM



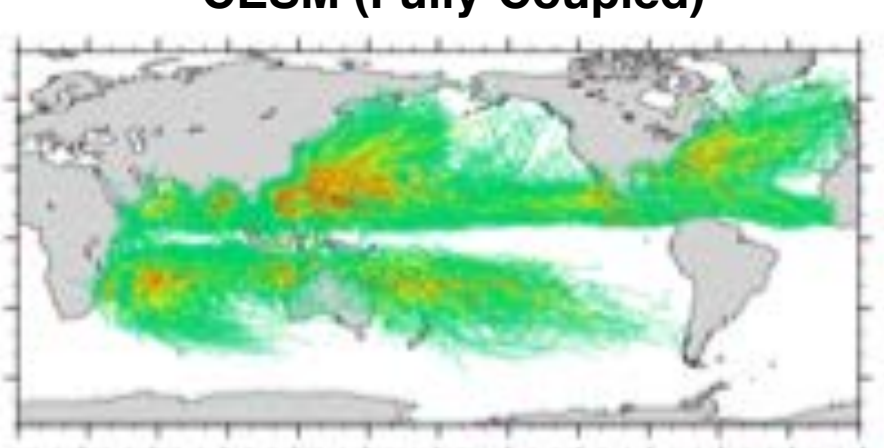
Li and Sriver, 2016 - JGR-Oceans

What the ocean sees

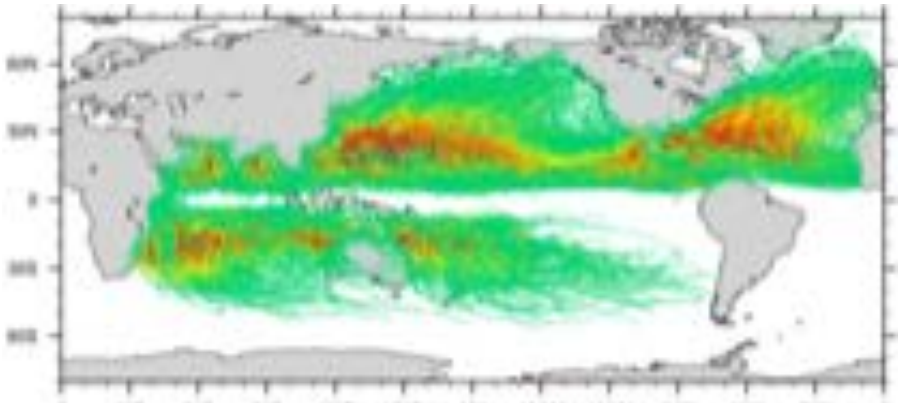
Some recent results

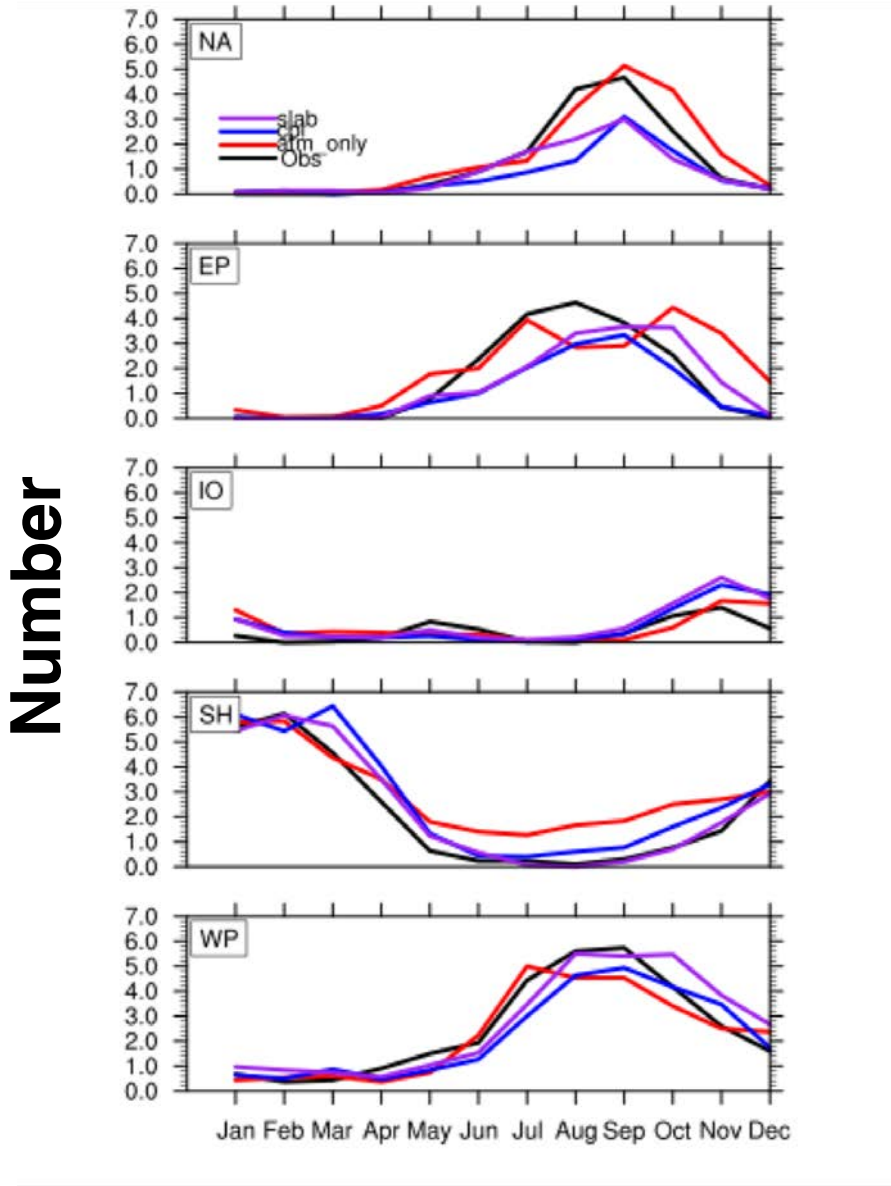
- **Both coupled and uncoupled versions of CESM simulate realistic spatial patterns and key features of the annual cycle.**

CESM (Fully-Coupled)



CESM (Atm-Only)





Li and Sriver (2018) — Journal of Advances in Modeling Earth Systems