Analyzing tropical cyclone-climate connections using the Community Earth System Model (CESM)

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Ongoing work supported by:

Blue Waters Symposium, Sunriver, Oregon, June 5, 2018

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?

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

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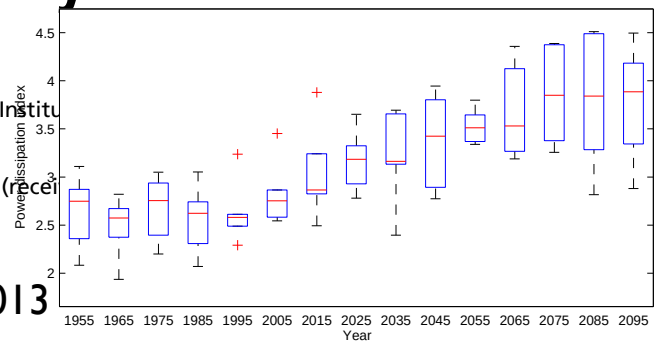


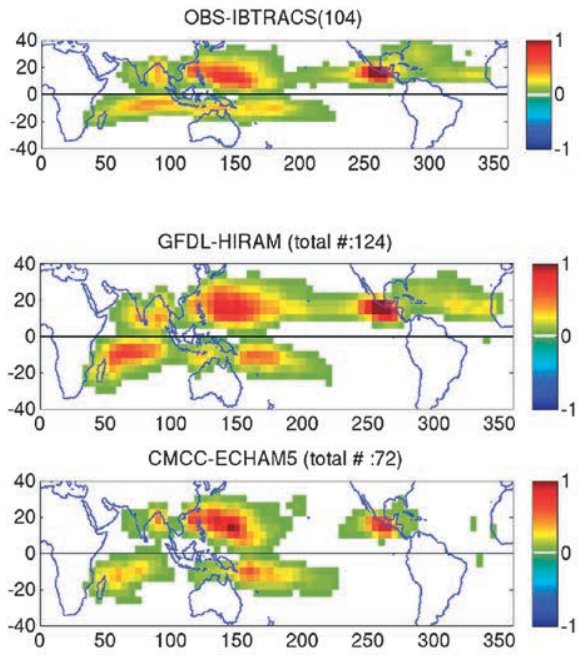
Emanuel, 2013

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 OOUCHI, 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.



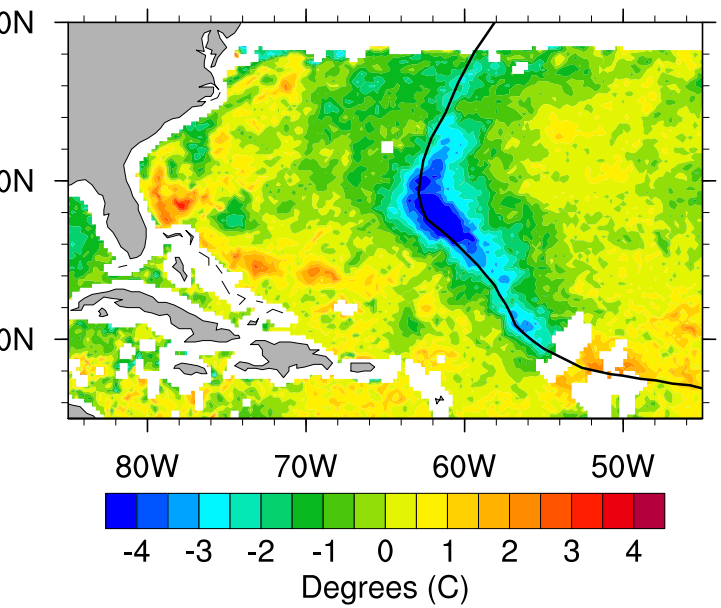
Walsh et al., 2015

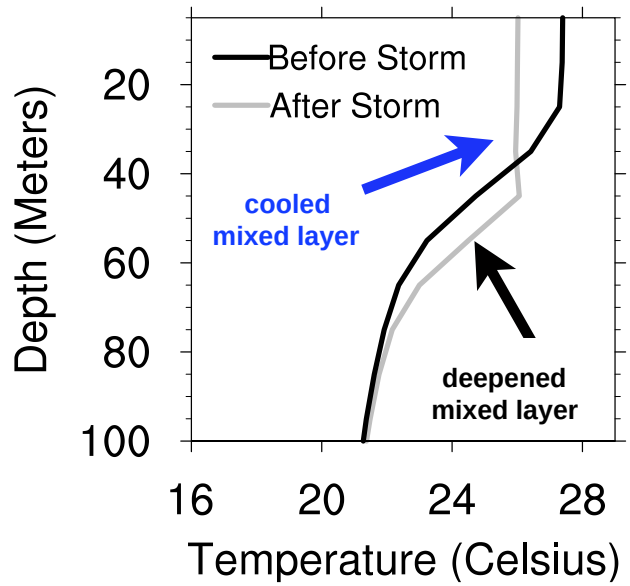
The question is difficult to answer with global models due to coarse resolution and lack of ocean-atmosphere coupling

Tropical cyclones play an active role in the climate system through enhanced ocean mixing by extreme surface winds

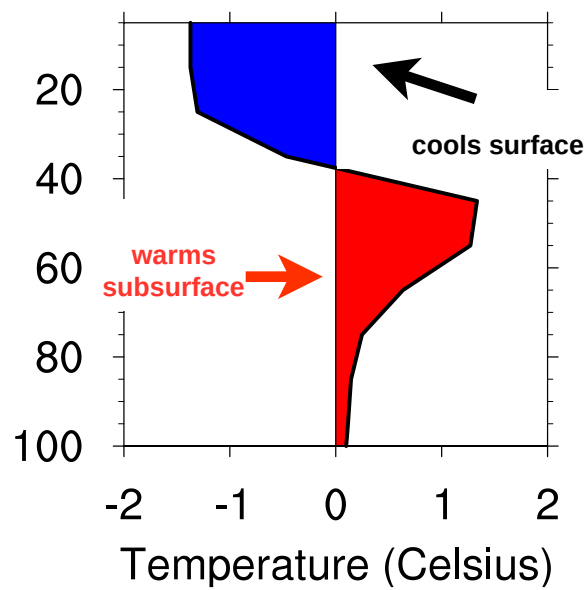
- Tropical cyclones tend to cool the surface ocean (primarily by vertical ocean mixing)
- TC-induced mixing redistributes heat vertically in ocean column (surface cooling and subsurface warming)

Hurricane Gert, 1999





post-storm minus pre-storm



Sriver, 2013 — PNAS

Short-term negative feedback

Surface cooling limits storm intensification (current and subsequent storms)

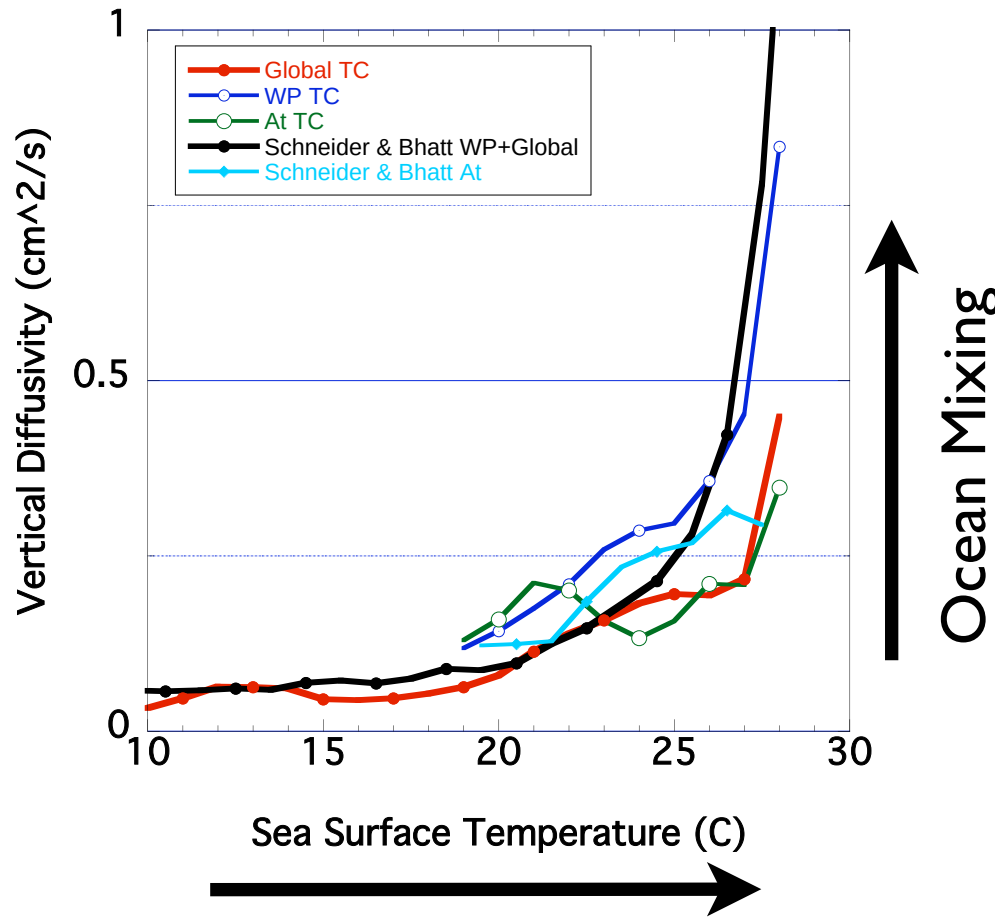
- days to weeks

Long-term positive feedback

Sub-surface warming provides additional energy for future storms

- months to years

On the global scale. TCs tend to cool the tropical oceans and contribute substantially to mixing and energy budgets



- Observations support positive relationship between SST and ocean mixing:
- A warmer ocean may experience more TC-mixing

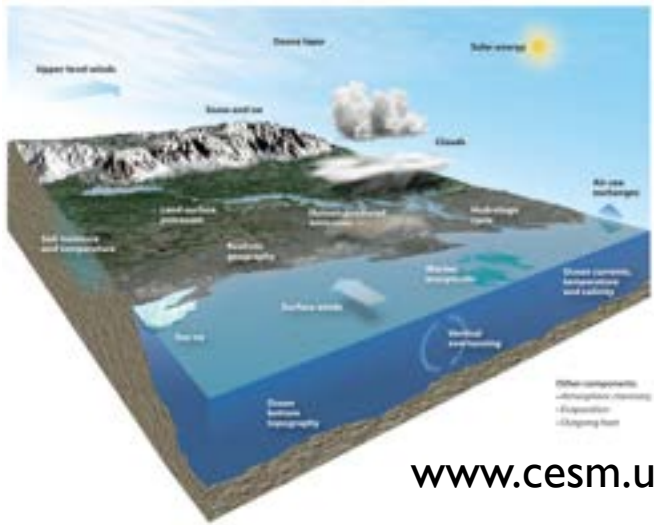
Sriver and Huber, 2007 — Nature

Sriver and Huber, 2007; Sriver et al., 2008

What did we do?

We use high-resolution configurations of the Community Earth System Model (CESM) to investigate the relationship between tropical cyclones, the upper ocean, and Earth's climate.

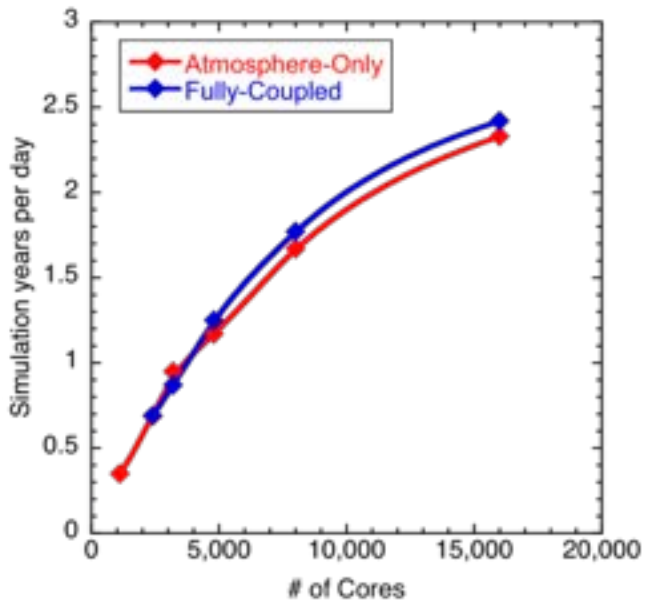
What is CESM?



www.cesm.ucar.edu

Numerical, deterministic global climate model that simulates the physics, dynamics, and interactions between:

- atmosphere (25 km resolution)
- ocean (1 deg resolution)
- land surface
- glaciers

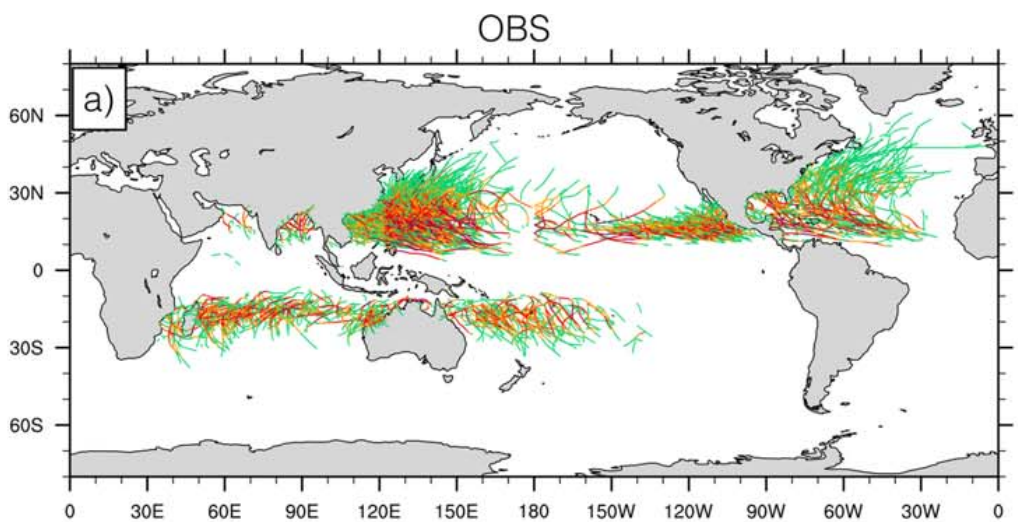


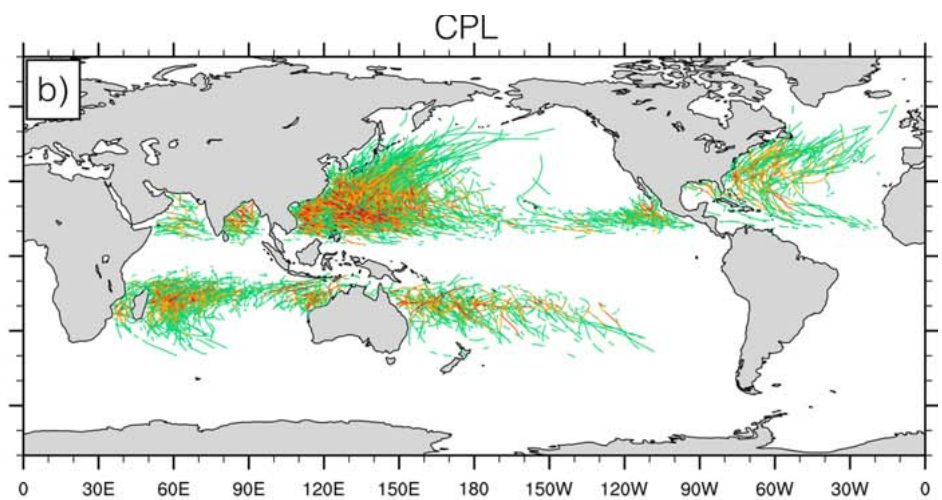
- CESM scales well on Blue Waters to ~15,000 cores
- We are adapting the model from other CESM projects — Susan Bates (NCAR) and Don Wuebbles (UIUC)

High Res CESM Experiment

3 multi-decadal pre-industrial control simulations using the 25 km atmosphere:

- Coupled Pre-Industrial Control (generates TCs within model)
- Atmosphere-only with ocean boundary conditions from coupled run
  - isolate effect of coupling on simulated TCs
- Ocean-only with atmosphere boundary conditions from coupled run
  - isolate effect TCs on upper ocean





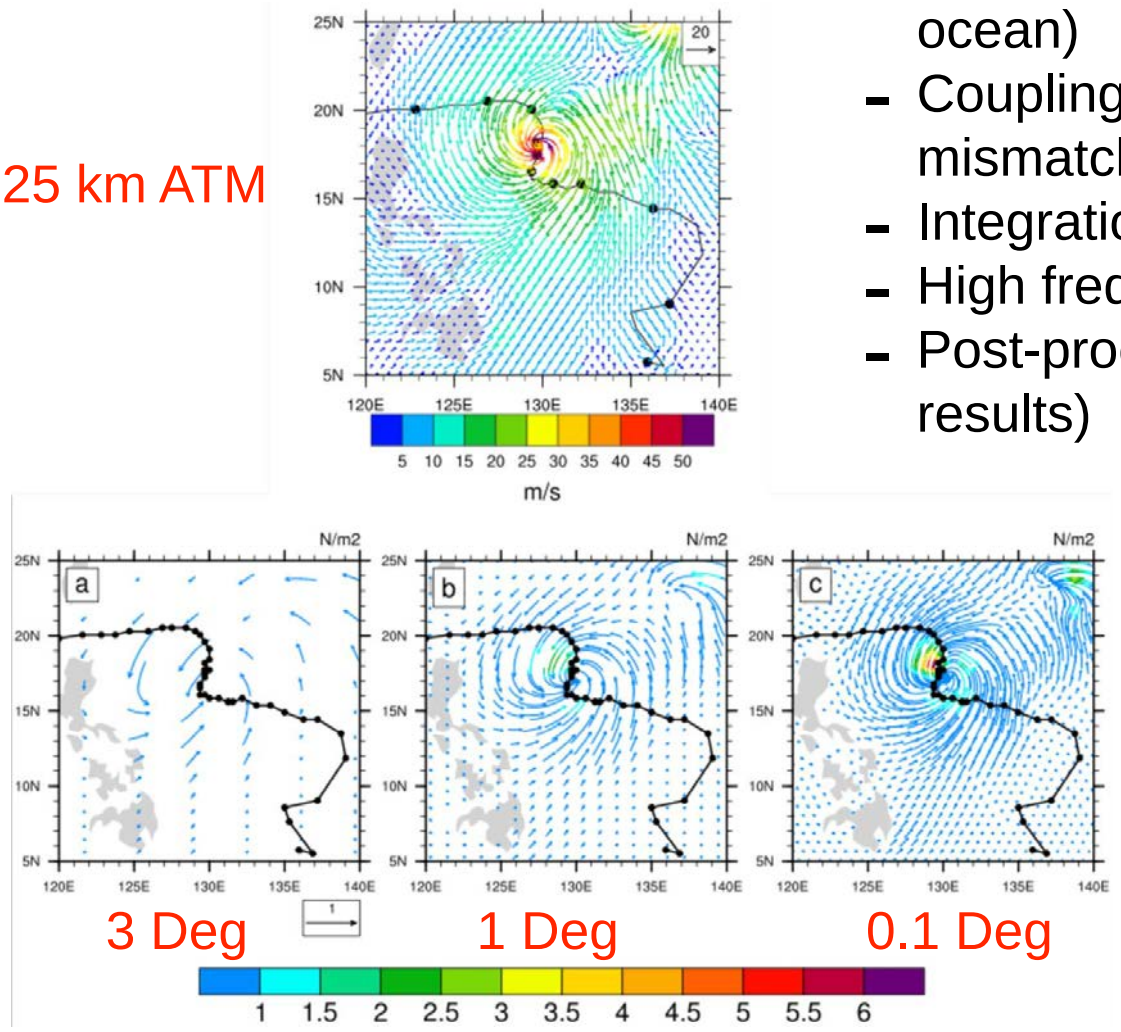
TC climatologies in coupled CESM generally agree with observations
- spatial distribution, timing, intensity

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

Major Challenges

- 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)

25 km ATM



What the ocean sees

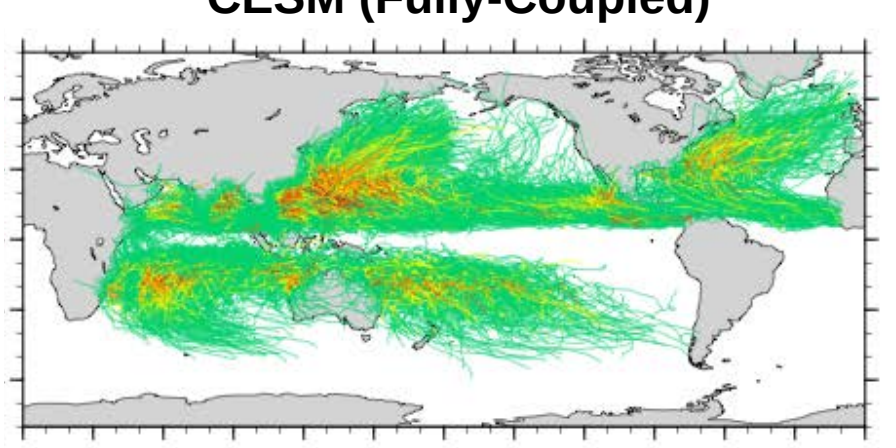
Li and Sriver, 2016 - JGR-Oceans

- Blue Waters provides the capabilities to overcome these challenges
  - Scalability; Large Allocations; Fantastic Researchers and Support

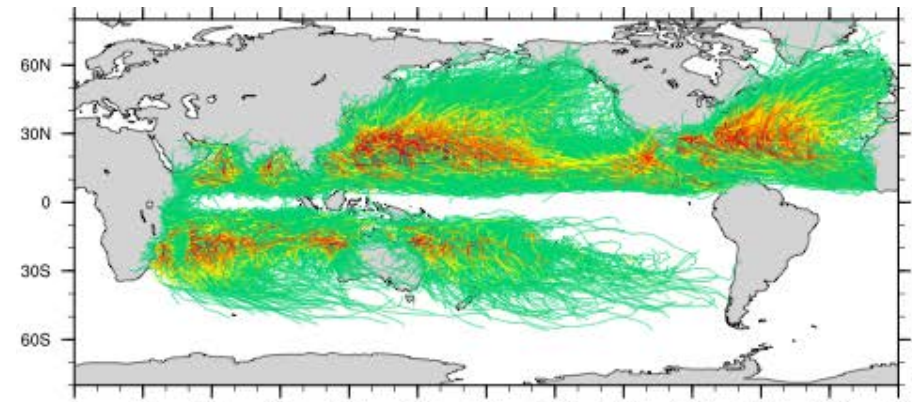
Some recent results

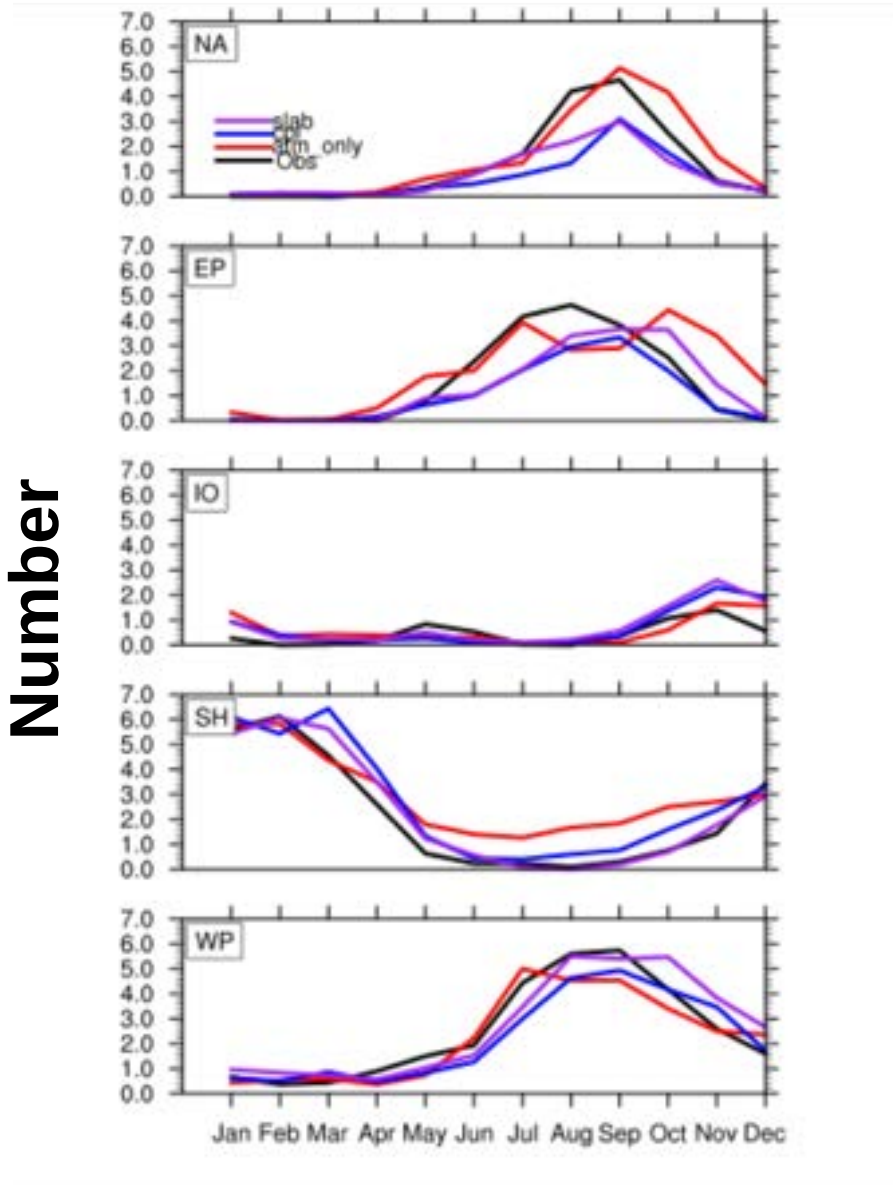
- **Both coupled and uncoupled versions of CESM simulate realistic spatial reasonably captures key features of the annual cycle.**

CESM (Fully-Coupled)



CESM (Atm-Only)

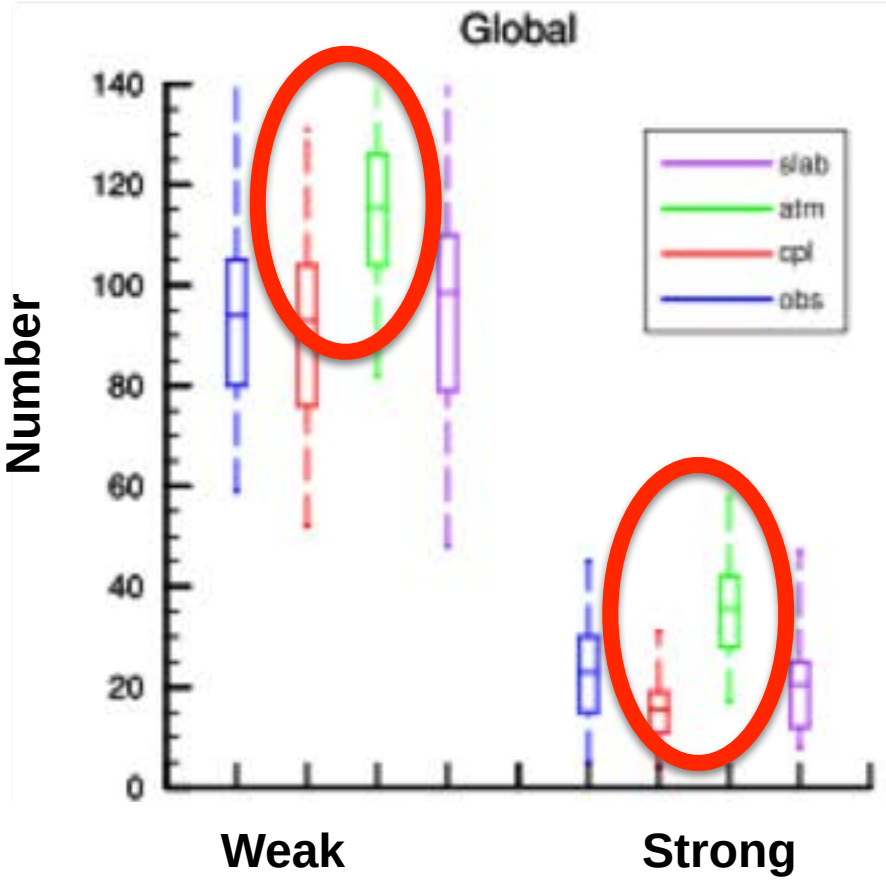


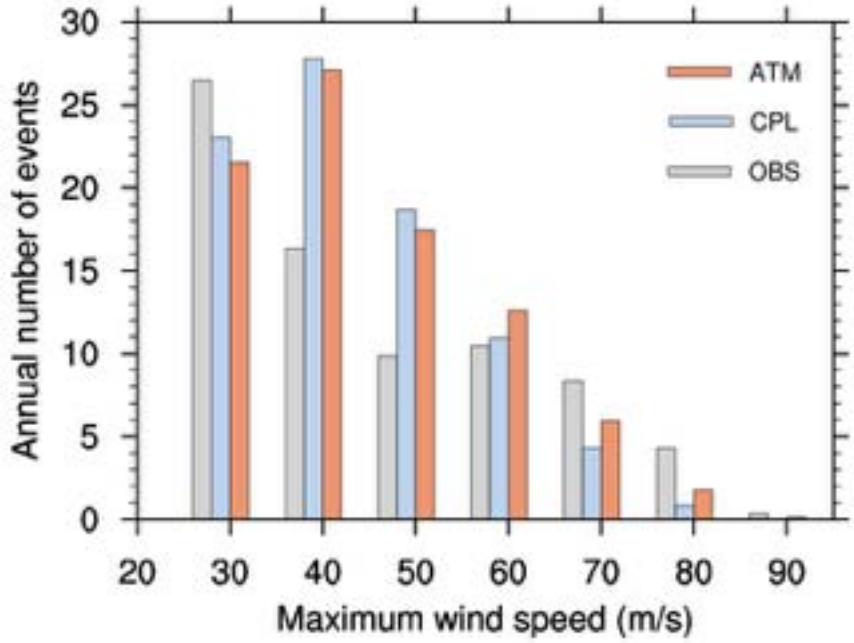


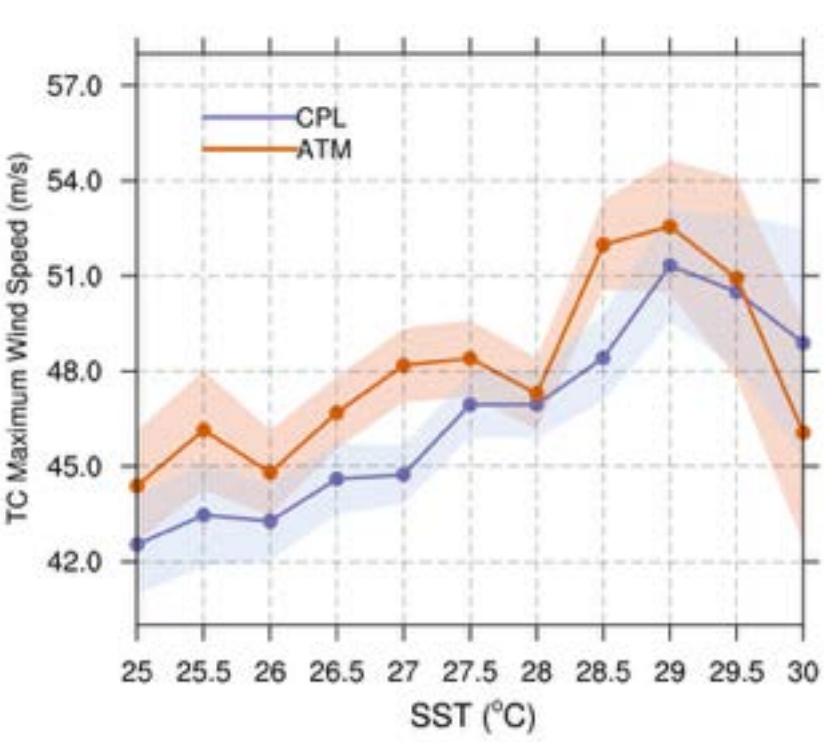
Li and Sriver (2018) — Journal of Advances in Modeling Earth Systems

Some recent results

We find generally more and stronger TCs in the atm-only simulation than coupled.





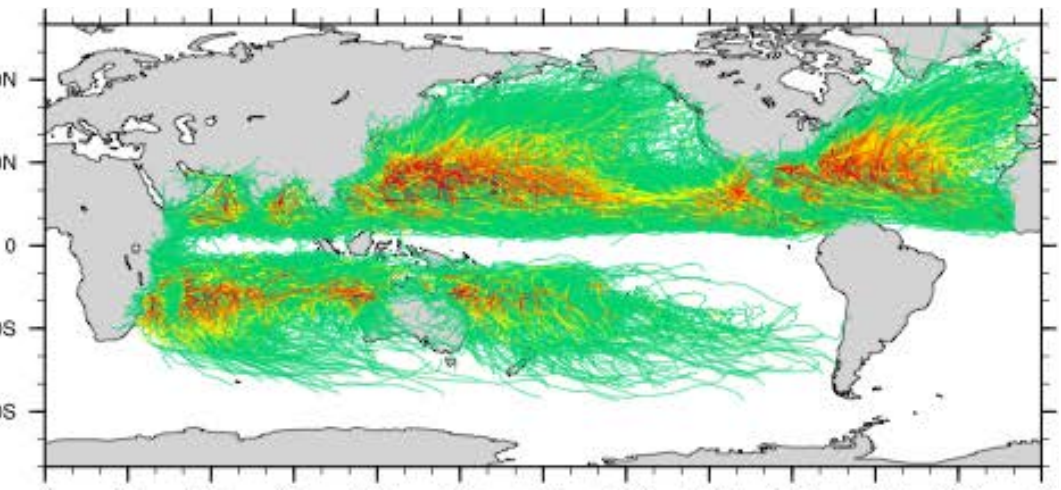


Differences in TC characteristics due to missing ocean-atmosphere interactions/ feedbacks

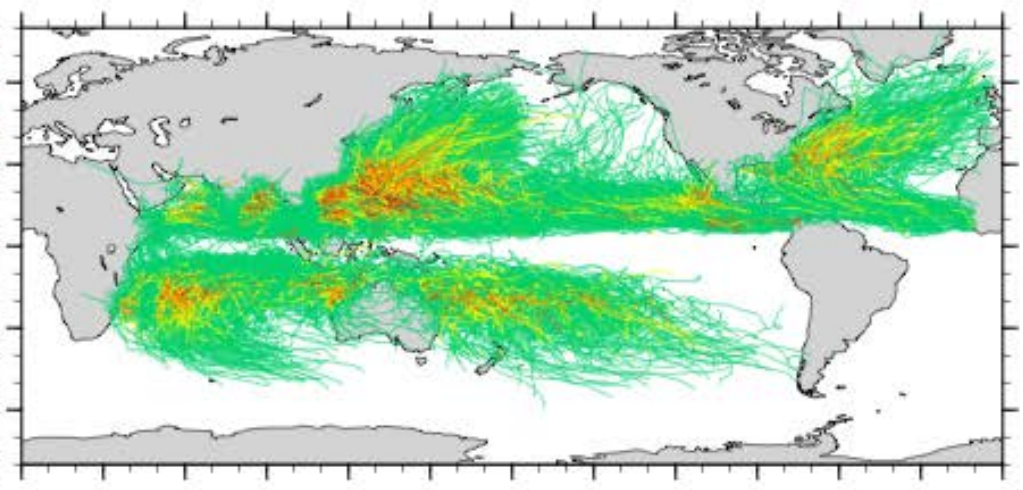
Li and Sriver (In Review)

Coupled ocean-atmosphere interactions influence tropical cyclone representation in CESM

CESM (Atm-Only)

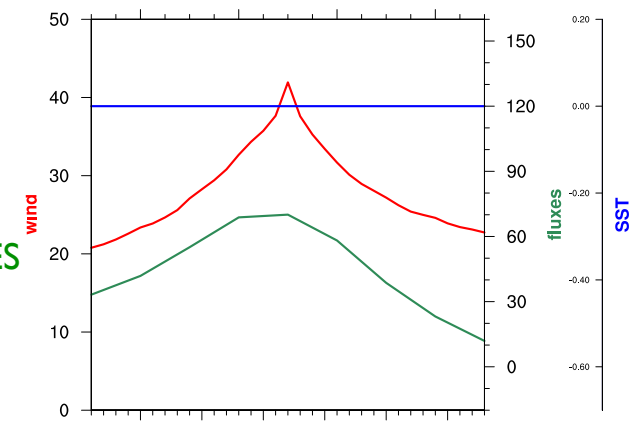


CESM (Fully-Coupled)



Atm-Only

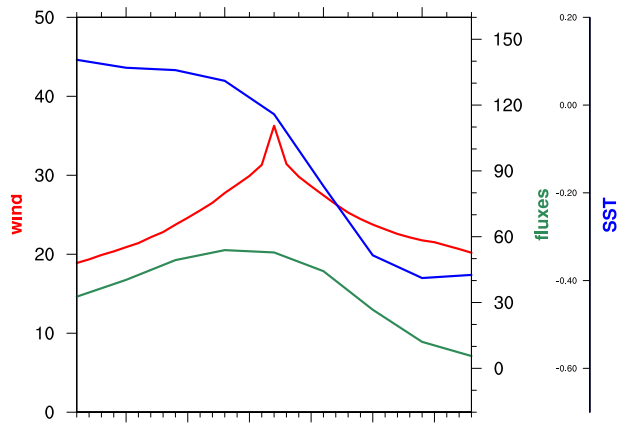
SFC TEMP
SFC WIND
SFC FLUXES



Time

Time evolution of average modeled storm conditions

Coupled

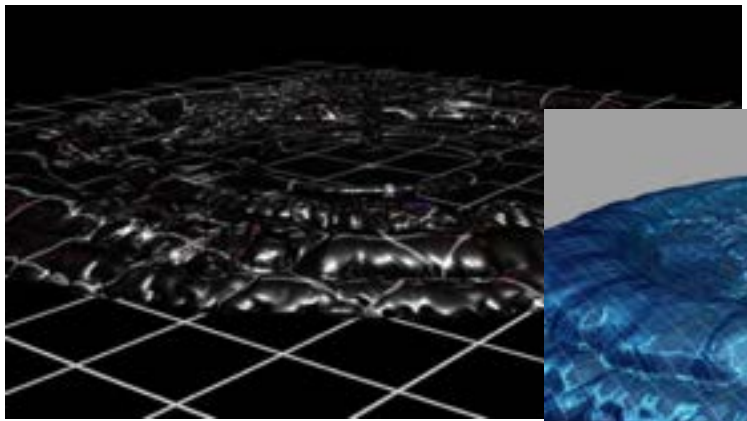


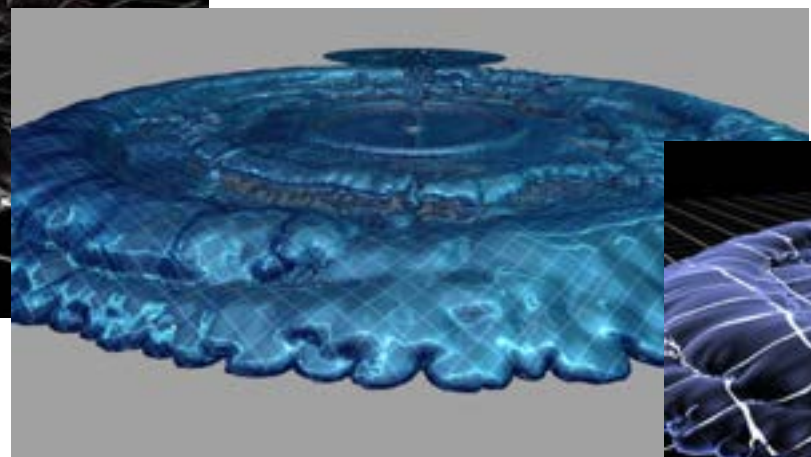
Time

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

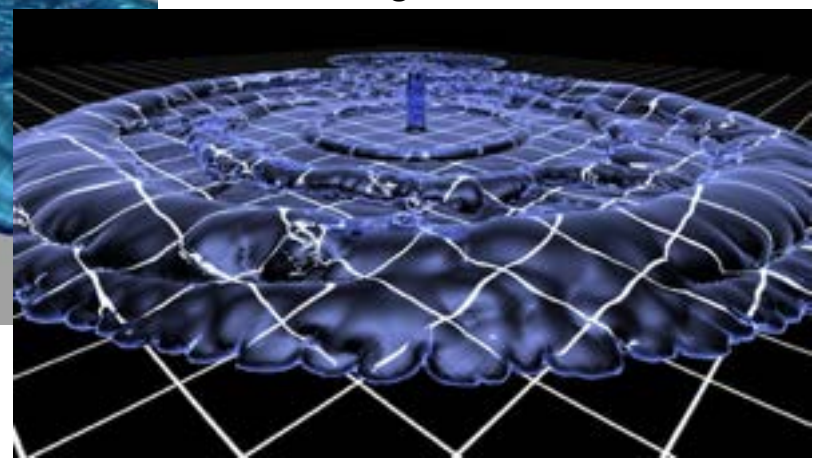
Li and Sriver (2018) — Journal of Advances in Modeling Earth Systems

We are working with the NCSA Data and Visualization Group to explore new ways to visualize big climate data (with a focus on TC-ocean interactions)

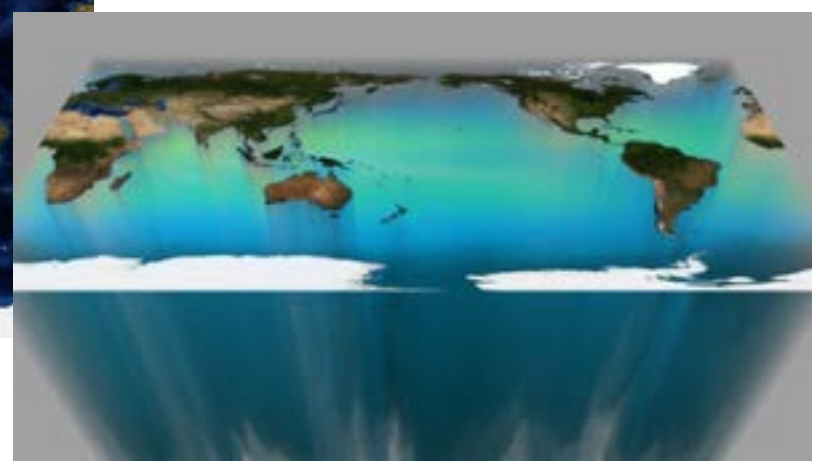




Visualizing Water Surfaces



Volume Rendering of the Ocean



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

Next Steps:

- **4xCO2 fully-coupled simulations branched from preindustrial control**
  - **Currently Running on Blue Waters**
  - **How do simulated TCs change with increased CO2?**

Some Conclusions:

- **We conducted a series of multi-decadal sensitivity experiments highlighting the importance of coupled ocean-atmosphere interactions in simulating realistic TC characteristics and basin-scale activity.**

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

- **Results point to the importance of coupled interactions in understanding the relationship between tropical cyclones and climate and paves the way for coupled modeling approaches exploring how tropical cyclone activity may change under anthropogenic global warming.**

Peer-Reviewed Publications:

- Li, H. and Sriver, R. L. (In Review), Impact of tropical cyclones on the global ocean: Results from multi-decadal global ocean simulations isolating tropical cyclone forcing, Journal of Climate.
- 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.
- 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. (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.

Conference Proceedings:

- Bock, D., Li, H. and Sriver, R. L. (2017), Simulation and visual representation of tropical cyclone-ocean interactions, The International Conference for High Performance Computing, Networking, Storage and Analysis (SC17), Denver, CO