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# Hybridizing Knowledge-Based and Machine Learning Models for Climate and Tipping-Point Prediction: Progress with Developing Hybrid Climate Model


Presented by
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# Focus of Current Efforts

- Climate change is necessarily a nonstationary process.

- We have developed machine learning techniques for prediction of non-stationary systems. (See Patel et al., Chaos 31, 033149, and arXiv:2207.0051 [cs.LG]) our goal is to incorporate these techniques into a realistic hybrid ML/knowledge-based climate model (Troy will show first preliminary results)

- We have been gradually adding new capabilities to the ML/knowledge-based climate model. Most importantly: dynamical coupling between the sea surface temperature (SST) and the atmosphere

# Two Approaches to Incorporating Ocean Dynamics into our Hybrid Atmospheric Model

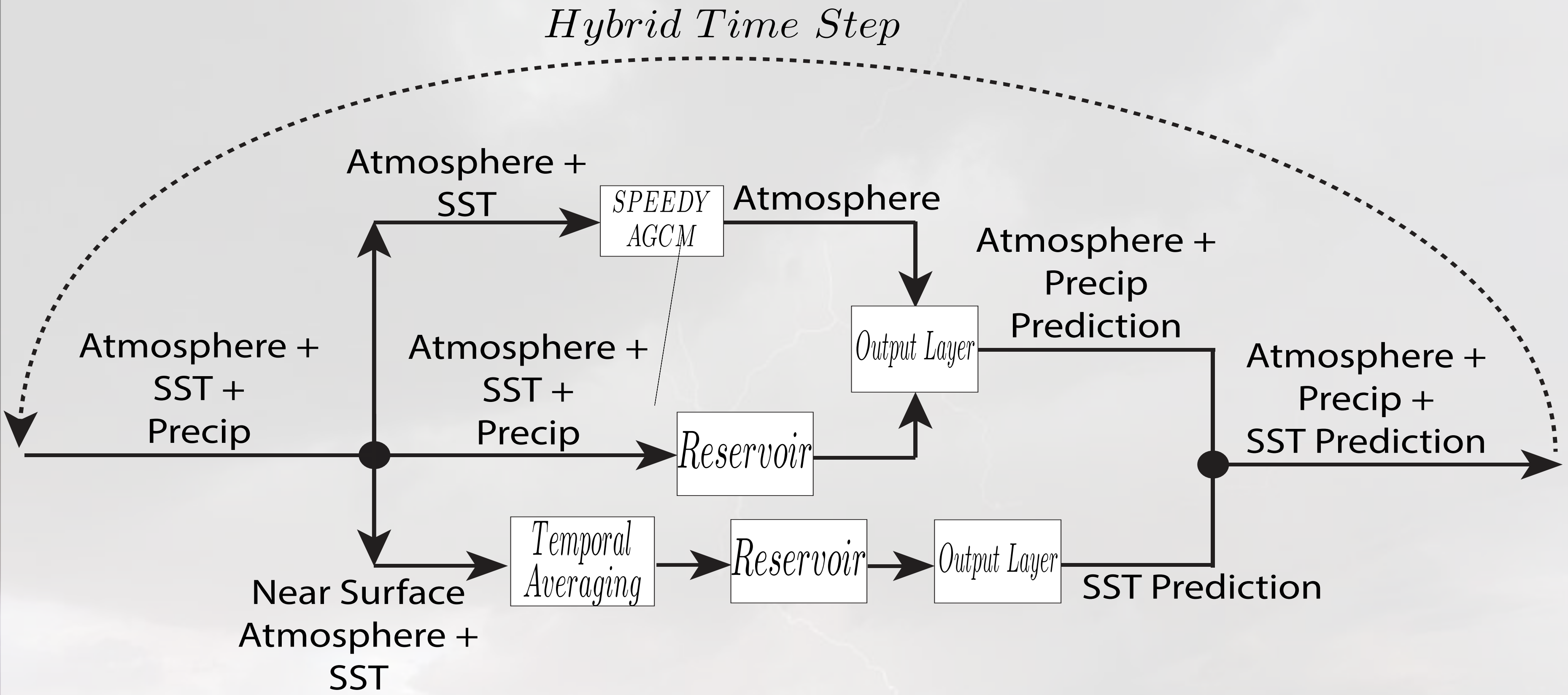
- **Approach I: ML model of the SST coupled to our hybrid ML/knowledge-based atmospheric model**

- **Approach II: Hybrid model of the SST using a thermodynamic model as the knowledge-based component**

- **Both approaches are being validated by simulating present climate**

- **Non-stationarity of the climate can be introduced in both approaches by varying a model parameter**

# Combining A Machine Learning Ocean Model with a Hybrid Atmospheric Model



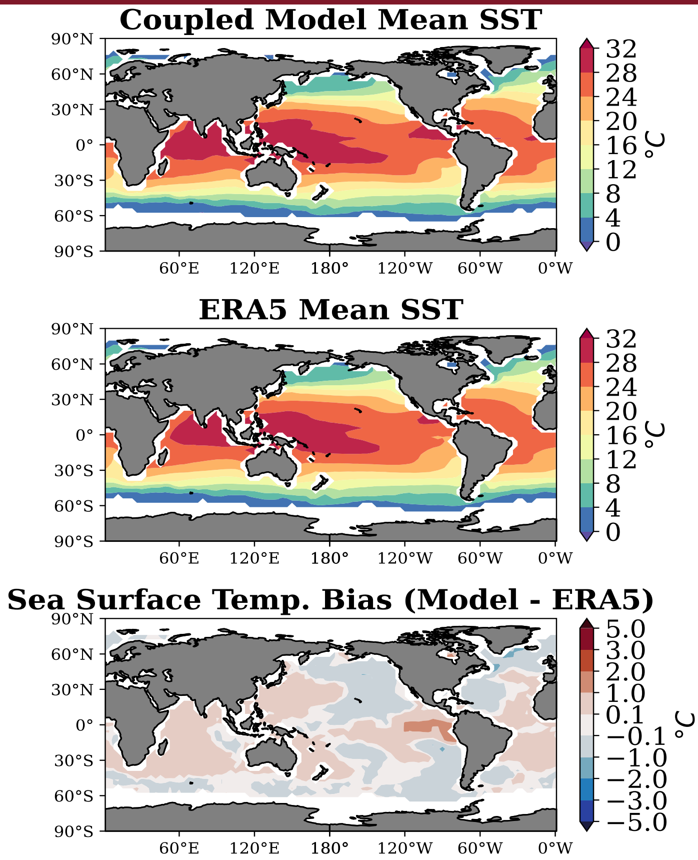
# Climate Simulation

- Both the atmosphere and ocean models are trained "offline" using 26 years of ERA5 data (1981-2007)
  - The hybrid atmospheric model is trained to make 6-hour forecasts
  - Ocean model is trained to make 7-day SST forecasts
- The coupled model is run for 70 years
  - No sign of instability

# Ocean Climatology

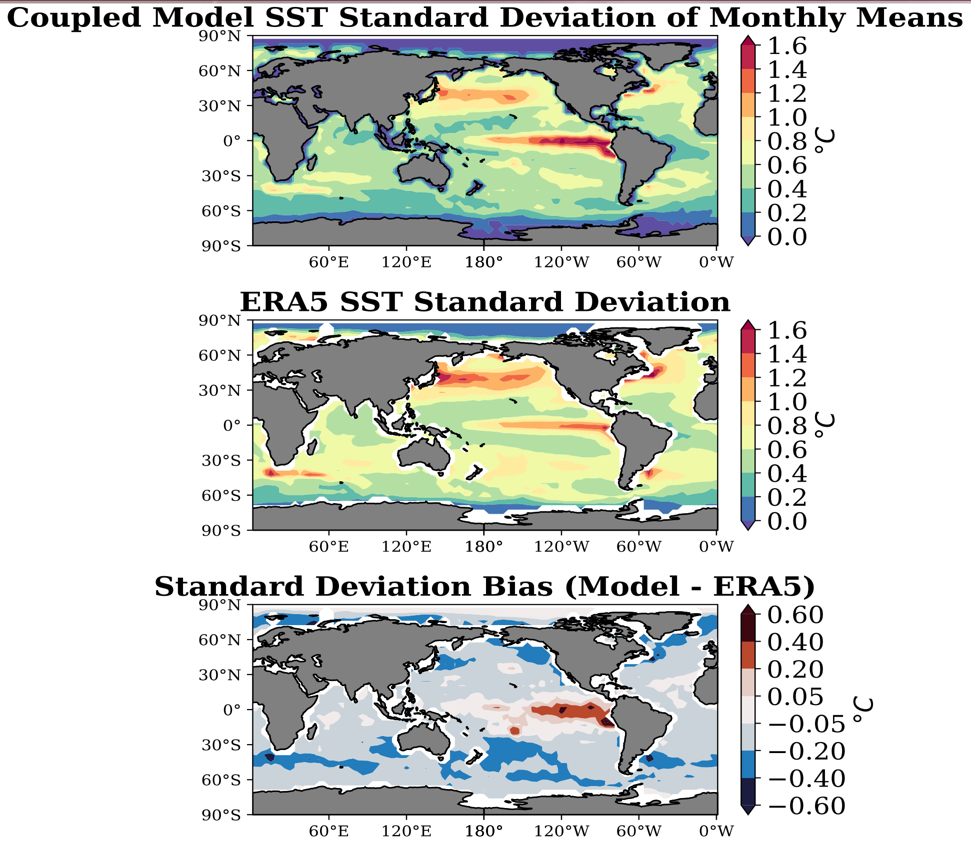
- **The ML-only model can reproduce the annual climatology**

- **Biases when compared to ERA5 are small**
  - **Better than state-of-the-art climate models with full ocean models**

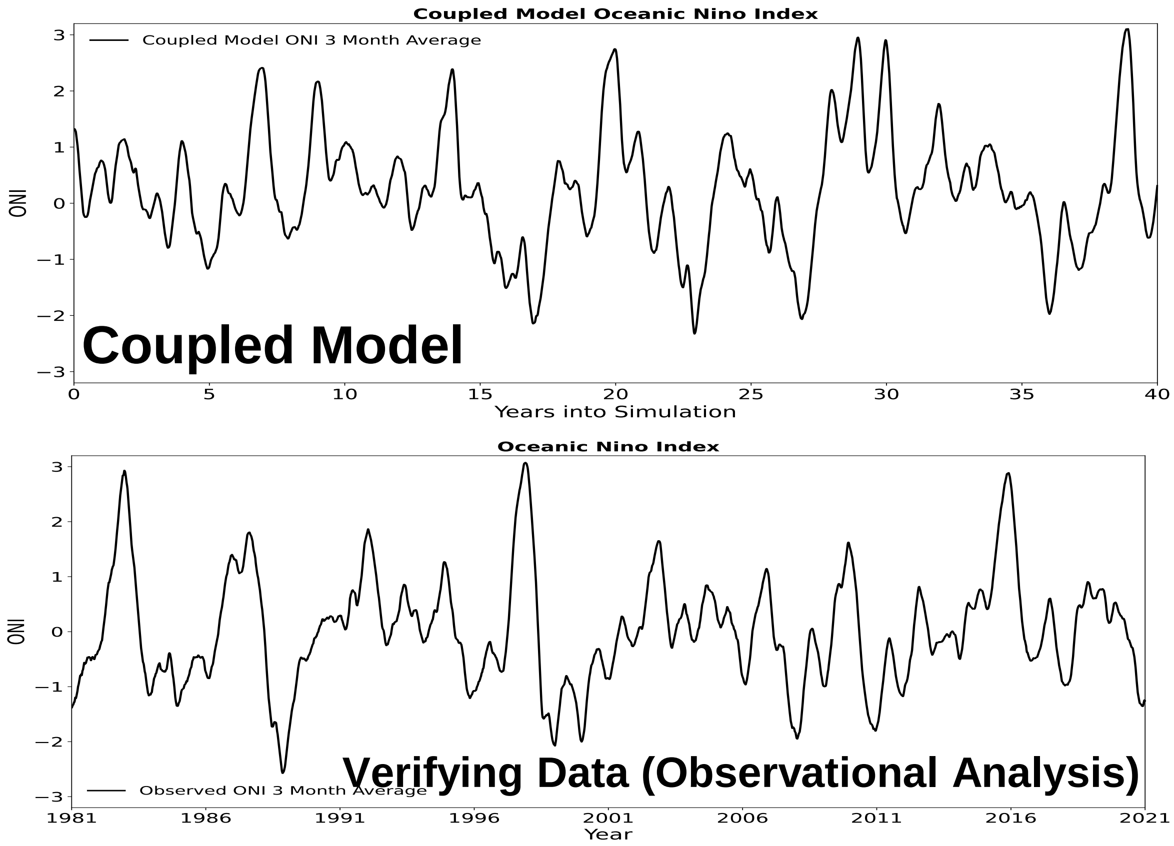


# Ocean Climatology

- The ML-only model can reproduce ocean variability
  - Average standard deviation of the monthly means during the 70-year free run
  - Compared to ERA5 (1981-2021)
  - Captures major ocean currents and extension regions (e.g. Gulf Stream and Kuroshio Extension)



# A Test of Our Coupled Model's Ability to Capture Ocean-Atmosphere Dynamical Interaction: ENSO




- **Coupled model produces realistic ocean and atmospheric response to ENSO**

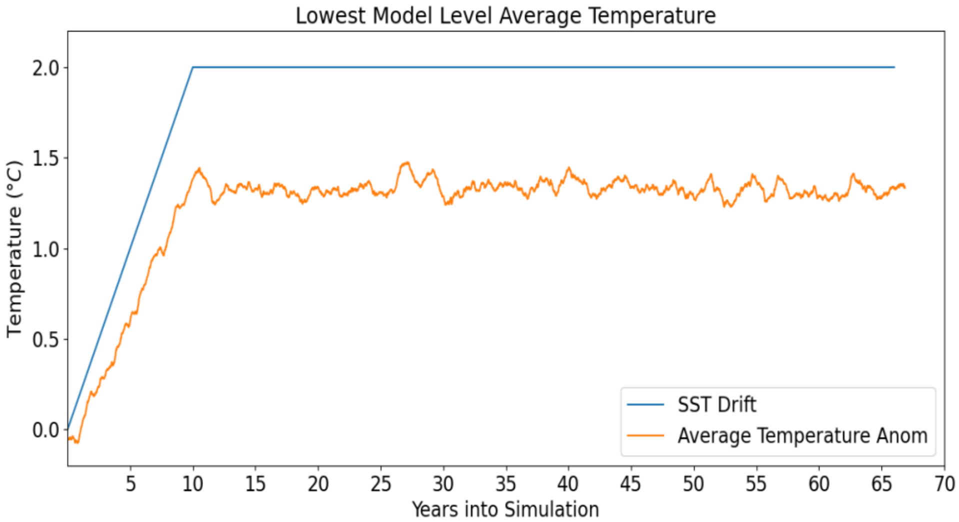
# Next Step: Incorporating Nonstationarity in Hybrid Model

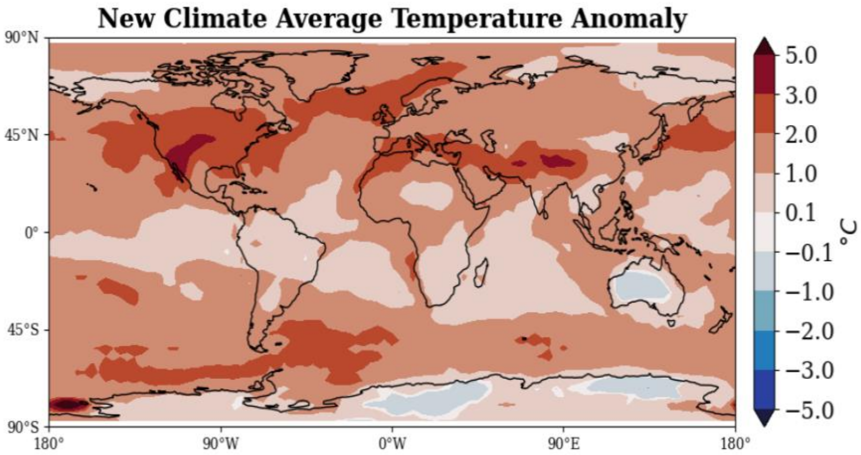
- Can the hybrid atmosphere-only model trained on the past and present climate extrapolate to a new climate?

- Our past work (Patel et al., Chaos 31, 033149, and arXiv:2207.0051 [cs.LG]) allows for the input of hypothetical nonstationary forcing into a hybrid model
  - We ultimately intend to do this for the hybrid coupled model with CO2 forcing

- As a first step, we have performed a preliminary series of experiments with our already-trained hybrid atmospheric model where the SSTs rise according to a hypothetical scenario

# Hybrid Atmosphere with Nonstationary SST (VERY Preliminary)




- **The SST boundary conditions in the SPEEDY component of the trained hybrid are adjusted by:**
  - **[New SST] = [Current SST Climatology] + [assumed drift (blue curve)]**
- **The hybrid model is stable during this new climate**
  - **Shows nonstationary response**

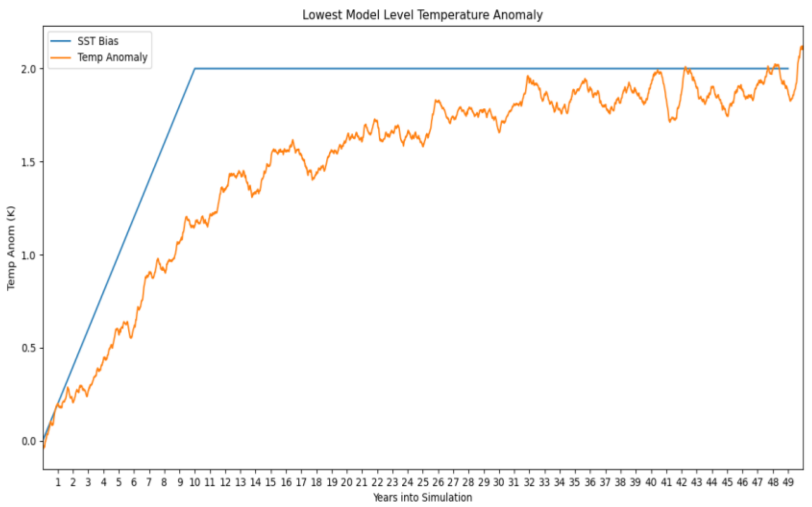
# TAKE AWAYS

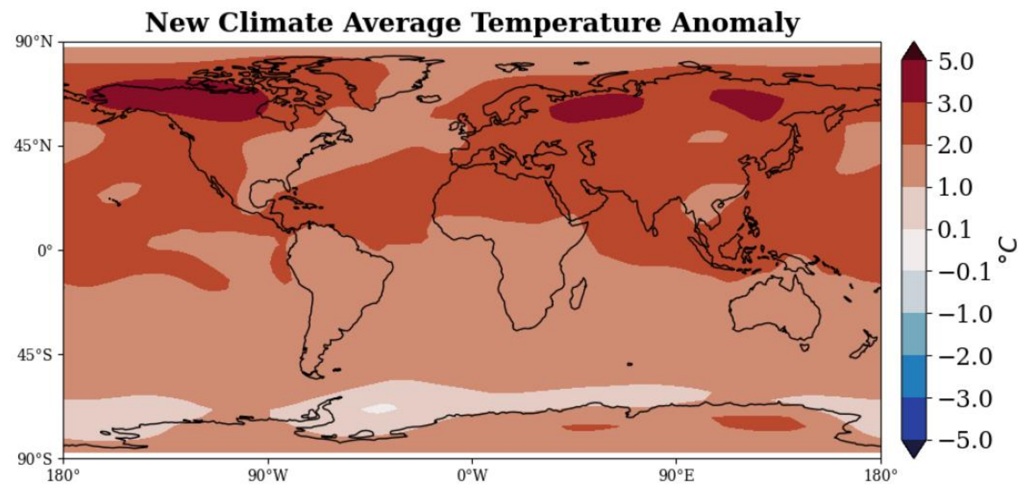
- Our hybrid ML/Knowledge-based climate model shows the potential for benefits with respect to accuracy and computational speed.

- Machine learning can be used to model and couple components of the Earth System
  - Able to capture interactions between the atmosphere and ocean (ENSO)
  - Our coupled model can be run at a small fraction of the computational cost compared to state-of-the-art numerical models

- Preliminary results show our coupled model can respond to a nonstationary signal and produce stable predictions

# SPEEDY Reference Experiment




- Simulation of hypothetical climate change situation
  - New SST = Current SST Climatology + assumed drift (blue curve)
- Hypo linear drift term over 10 years until it plateaus at 2K