Machine Learning for Atmospheric Modeling

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Outline

Atmospheric Models

An Atmospheric Model: The computer code implementation of a **mathematical algorithm** to model the spatiotemporal **evolution of the atmospheric state**

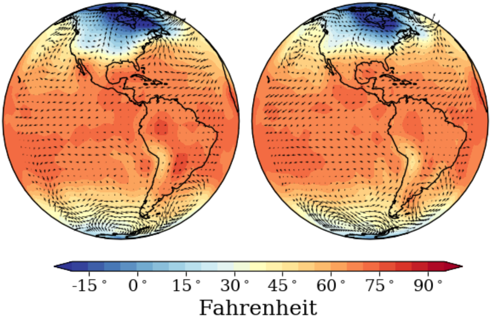


Illustration: (Left) Atmospheric state at time *t*, (Right) Model prediction of the atmospheric state for time *t*

- Specific **purposes of atmospheric modeling** considered in this talk:
  - **Weather prediction**
  - **Climate Simulations**
- **Weather prediction** has always been a **big data problem** requiring **new technologies** and **novel ideas** to use them.
- For example, he first official U.S. weather forecast was issued on February 19, 1871, which was made possible by
  - the availability of a new technology called the **telegraph** (patented in 1837 and first used to send a message in 1844 by Samuel Morse)
  - the organization of a **network of observing stations**, and
  - the development of a **coding system** to transmit the observations by telegraph

Physics-Based (Numerical) Atmospheric Modeling: Part I

- The **vision of physics- (fluid dynamics-) based weather prediction:** (Cleveland Abbe, 1901), and (Vilhelm Bjerknes, 1904)
- **First numerical algorithm** to solve the physics-based model: Lewis Fry Richardson (1922): *Weather Prediction by Numerical Process,* Cambridge University Press.

From P. Lynch, 2006; Artist: Francois Schuiten: "After so much hard reasoning, may one play with a fantasy...": in Richardson's "forecast factory", 64,000 human computing units work to keep up with the speed of the real atmosphere

Physics-Based (Numerical) Atmospheric Modeling: Part II

- **First successful implementation** of a numerical atmospheric model on a **digital computer** (ENIAC-Electronic Numerical Integrator and Computer): (Charney et al. 1950)
- **Operational numerical weather prediction** started in Sweden in December 1954 (on a Binary Electronic Sequence Calculator (BESK) computer)
- Operational numerical weather prediction **in the U.S.** started on May 6, 1955 on an IBM-701 Defense Calculator (speed: 1 Kflops)

The Use of ML in Atmospheric Modeling

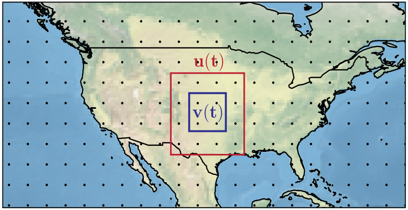
- **ML-based Model Components** were first considered in the 1990s (e.g., Krasnopolsky et al., 2005)
  - ML is used **(i)** to **parameterize** processes **unresolved** by the model physics, or to **(ii)** **emulate** **computationally expensive components** of the model physics
  - Training data can be produced by “higher-resolution” model simulations or based on observations
- **ML-only Models** started to appear in the literature in the last few years (e.g., Pathak et al. 2022)
  - Typically trained on **reanalysis data**: observational analyses available for decades with 1-6 h temporal resolution
  - Observational analyses are obtained by **data assimilation**: filtering tens of millions of observations per day with the dynamics of a state-of-the-art numerical model
- **Our Hybrid Approach** (described next)

Collaborators

- Troy Arcomano (TAMU Ph.D. student)
- Mitchell Tsokatos (TAMU MS student)
- Edward Ott (UMD Distinguished University Professor)
- Brian Hunt (UMD Professor)
- Alexander Wikner (UMD Ph.D. student)

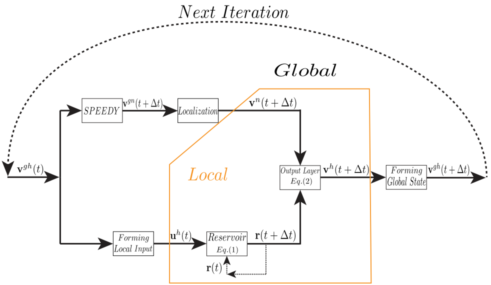
Our Approach: Combined Hybrid-Parallel Prediction (CHyPP)

- All results are for a **prototype hybrid model** (Arcomano et al., 2022) that implements **CHyPP** (Wikner et al., 2020) on a low resolution atmospheric general circulation model called **SPEEDY** (Molteni and Kucharski, Verison 41)
- ML component is based on **Reservoir Computing**(e.g., Lukosevicius and Jaeger 2009)



Source of **high scalability**: all ML calculations are done for local subdomains of flexible size (e.g., blue rectangle) in parallel

Flow Chart of the Hybrid Model



$$\mathbf{r}(t + \Delta t) = \tanh\left[\mathbf{A}\mathbf{r}(t) + \mathbf{B}\mathbf{u}^{h}(t)\right], \tag{1}$$

A: a **weighted adjacency matrix** of a low-degree, directed, random graph

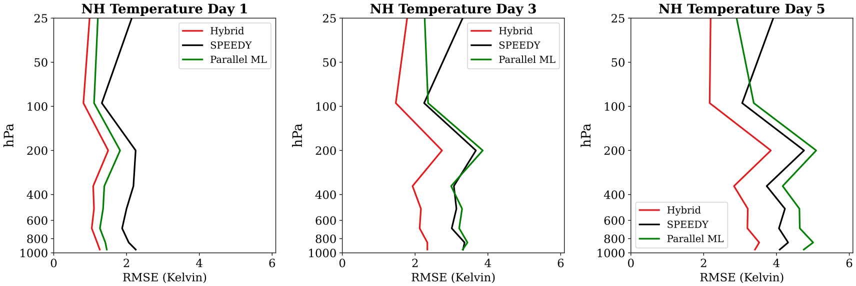
$$\mathbf{u}(t + \Delta t) = \mathbf{W}\tilde{\mathbf{r}}(t + \Delta t), \tag{2}$$

$\tilde{\mathbf{r}}(t)$: a (possibly nonlinear) function of $\mathbf{r}(t)$; **W** is a **matrix of parameters** **to be determined by training**

Forecast Experiments

- **Training Data:** ERA5 (a 5th generation reanalysis data set) from 1 January, 1990 to 26 June, 2011
- **“Time Step":** 6 h
- **Forecasts:** 100 21-day forecasts equally spaced in time between 27 June, 2011 and 28 July, 2012
- **Forecast Verification Data:** ERA5 reanalyses
- **Benchmark Forecasts:**
  - **SPEEDY**
  - **ML-only** (Arcomano et al. 2020)

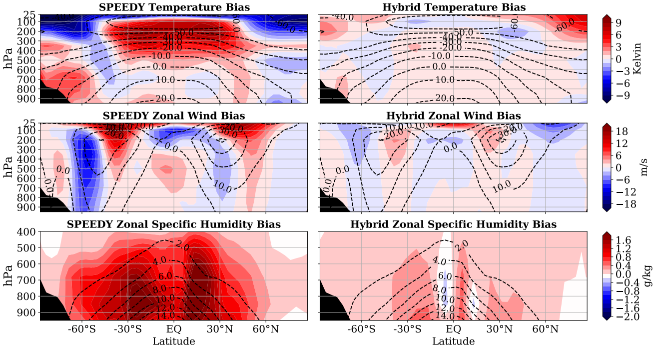
Example for Verification Results: NH Midlatitudes Temperature



The **hybrid forecasts** are **more accurate** than either the numerical forecasts or the ML forecasts

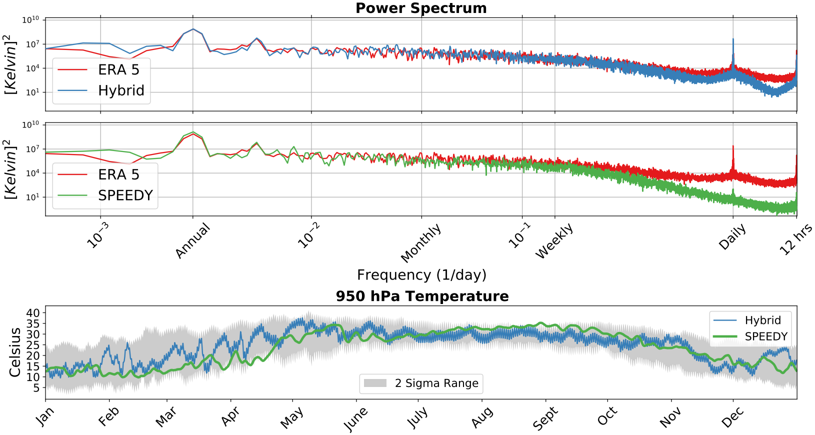
Climate Simulation Experiment: Biases

- Training: 19 years of ERA5 data (January 1981-December 1999)
- Simulation: 11-year free run with hybrid model (first year is discarded)



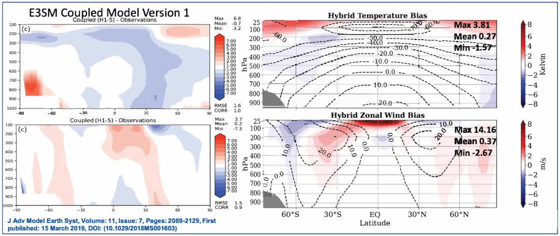
Boreal Winter (DJF)

Climate Simulation Experiment: Atmospheric Variability



925 hPa Temperature in the Sahara Desert

Climate Simulation Experiment: Comparison to a State-of-the-Art Earth System Model



	Temperature			
Model	Min Bias	Max Bias	Mean Bias	RMSE
SPEEDY	-6.56	7.11	0.83	3.22
E3SM	-3.24	6.87	-0.77	1.62
Hybrid	-0.92	2.38	0.19	0.49

	Zonal Wind			
Model	Min Bias	Max Bias	Mean Bias	RMSE
SPEEDY	-6.93	20.7	0.63	2.30
E3SM	-7.38	3.79	-0.26	1.53
Hybrid	-1.73	1.83	0.12	0.60

Concluding Remarks

- While most applications of ML to atmospheric modeling are still in the research phase, it is obvious that **ML techniques will soon play a big role** in atmospheric modeling.
- ML has the potential to lead to **major changes in** the roles of the different members of **the weather and climate enterprise**.
- Results from our research suggests that a **hybrid approach** can produce models that can perform well in **both weather prediction and climate-related** applications.

All paper citations in this presentation are hyperlinks. Clicking on a citation will bring up the full paper in your browser.