# Learning to Predict Spatiotemporal Variability of Climate


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(Shinjae Yoo, Ji Hwan Park, BNL; C. Jiang, Amir Farimani, CMU)

# Outline

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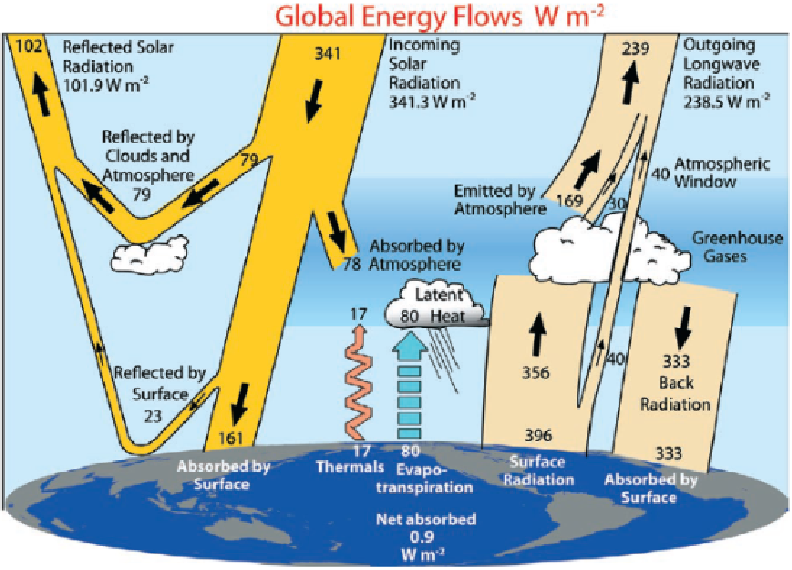
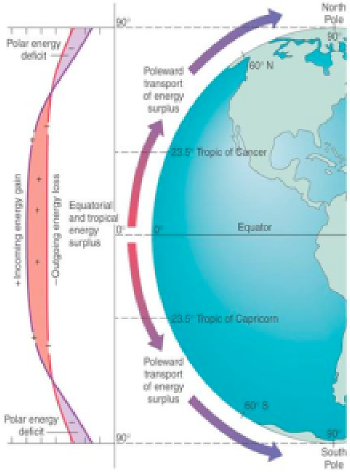



**Fig. 1.** The global annual mean Earth's energy budget for the Mar 2000 to May 2004 period (W m$^{-2}$). The broad arrows indicate the schematic flow of energy in proportion to their importance.

(Trenberth et al., 2009)

# Poleward Heat Transport




ttp://www.iupui.edu/ geogdept/g107/polderman/lectures/atmos-radiation.htm

- More Insolation (UV) in Equatorial and Tropical Regions than Polar Regions
- Outgoing IR more uniform
- This Energy Imbalance is Ultimate Driver of Atmospheric and Oceanic Circulation
- Inturn Transports Heat

# Meridional Distribution of Radiative Imbalance

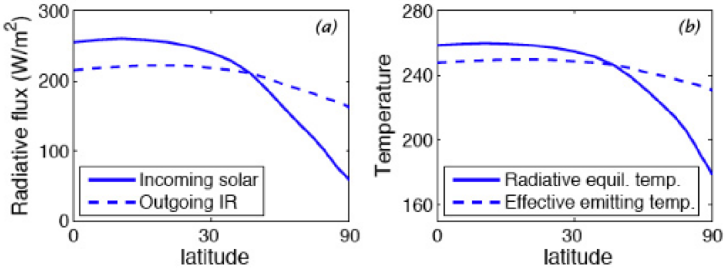
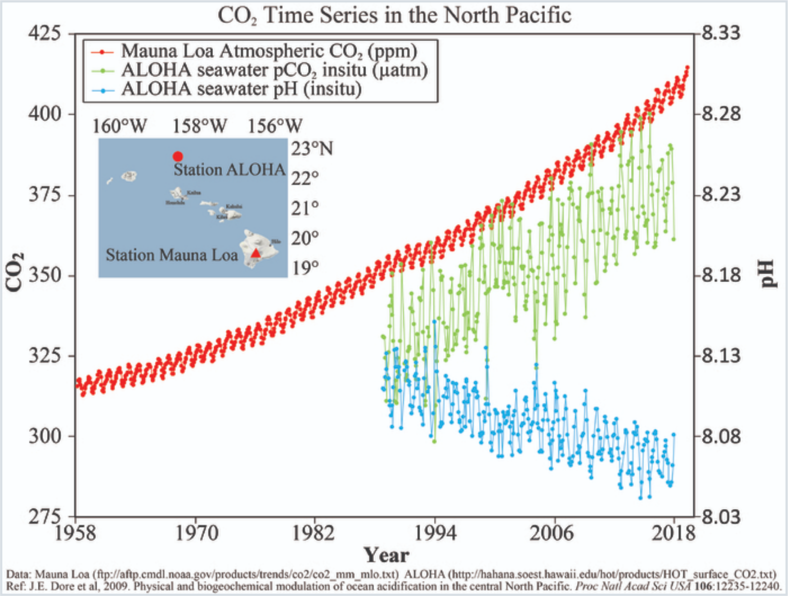
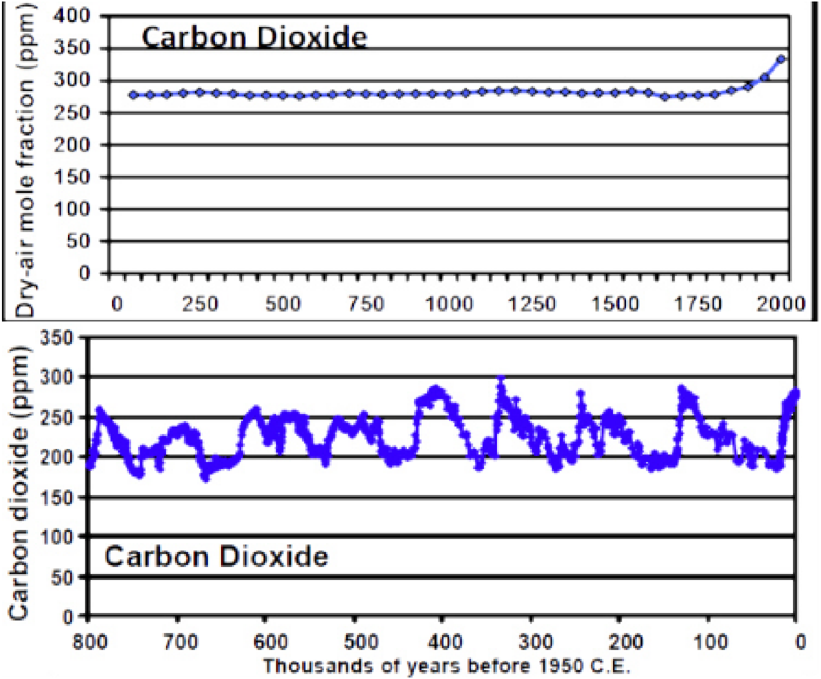



**Fig. 11.1** (a) The (approximate) observed net average incoming solar radiation and outgoing infra-red radiation at the top of the atmosphere, as a function of latitude (plotted on a sine scale). (b) The temperatures associated with these fluxes, calculated using $T = (R/\sigma)^{1/4}$, where $R$ is the solar flux for the radiative equilibrium temperature and $R$ is the infra-red flux for the effective emitting temperature. Thus, the solid line is an approximate radiative equilibrium temperature

Vallis, 2006

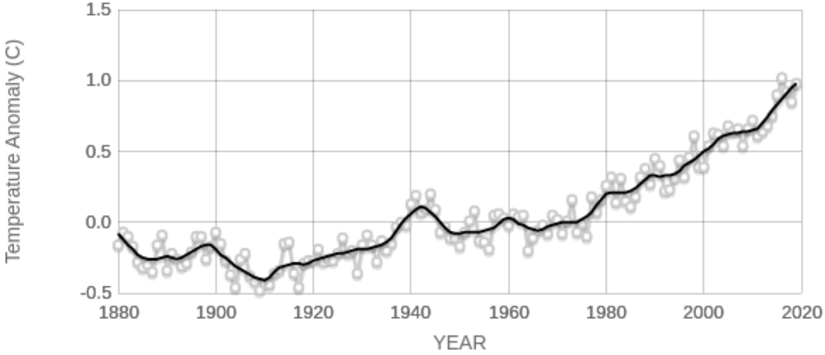
# Hawaii Carbon Dioxide Time-Series





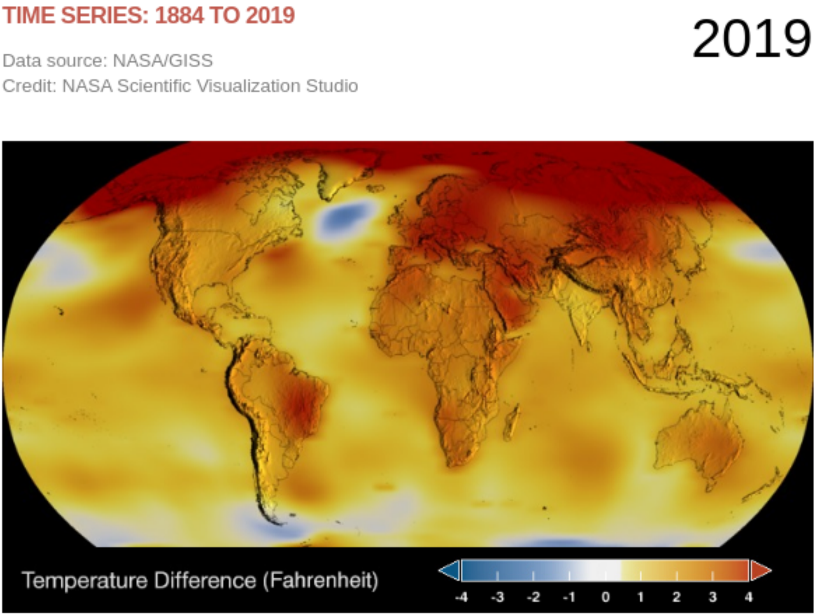

(Berkeley Lab)

# Temperature Response




Source: climate.nasa.gov

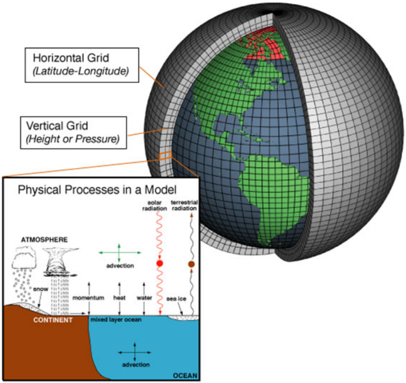
# Temperature Response



# Outline

# Earth System Models

- Built bottom-up by coupling various dynamical, physical, and biogeochemical subsystems
  - Atmosphere, ocean, sea-ice, land surface and vegetation, biogeochemistry in ocean
  - Closes carbon cycle
- Best tool available to understand and model climate and climate change




http://celebrating200years.noaa.gov/breakthroughs/climate_model/welcome.html

- Computationally demanding and requires big infrastructure
- Prevents it from being used even more widely and in different settings.

# What do Earth System Models *try* to do?

Basically everything that the climate system does: feedbacks, circulation, poleward heat transport, energy balance, temperature distribution everywhere, etc.

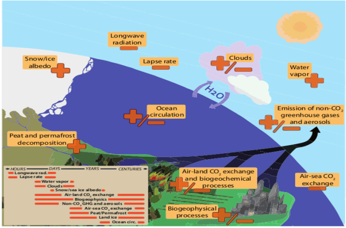
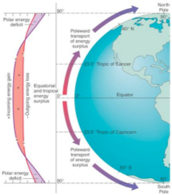



**Figure 1.2** | Climate feedbacks and timescales. The climate feedbacks related to increasing $CO_2$ and rising temperature include negative feedbacks (–) such as LWR, lapse rate (see Glossary in Annex III), and air–sea carbon exchange and positive feedbacks (+) such as water vapour and snow/ice albedo feedbacks. Some feedbacks may be positive or negative (±): clouds, ocean circulation changes, air–land $CO_2$ exchange, and emissions of non-GHGs and aerosols from natural systems. In the smaller box, the large difference in timescales for the various feedbacks is highlighted.

## Poleward Heat Transport

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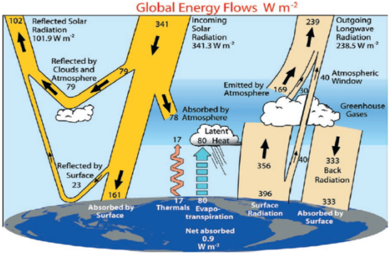


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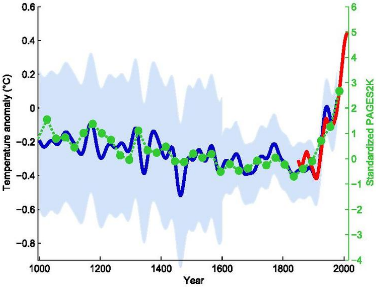

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# Prediction and Predictability

"Weather prediction is (then identified with) the process of determining how the weather will change as time advances, and the problem of weather predictability becomes that of ascertaining whether such predictions are possible."

# Climate Prediction and Predictability

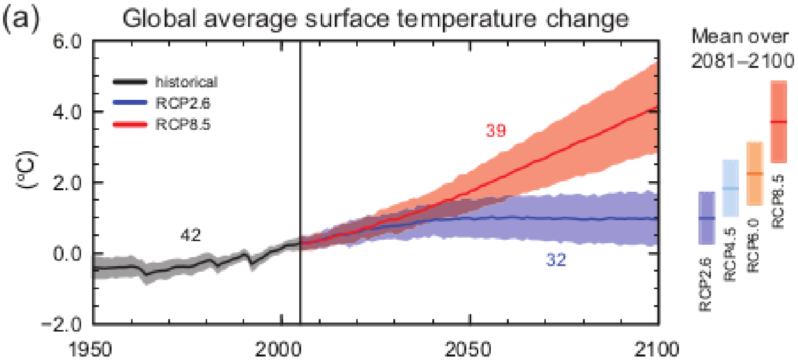
"Weather is (often) identified with the complete state of the atmosphere at a particular instant.

...We may therefore define climate as a set of statistics of the ensemble of all states during a long but finite span. Climate prediction then becomes the process of determining how these statistics will change as the beginning and end of the time span advance and climatic predictability is concerned with whether such climatic prediction is possible"

Lorenz, E. N. (1975). Climate predictability, The physical basis of climate and climate modelling (vol. 16, pp. 132–136), Garp publication series: WMO.

# Outline

# Models Good at Realizing External-Forcing Related Predictability
(IPCC AR5)




Note that as much as 93% of excess heat due to GHGs is taken up by the world oceans!

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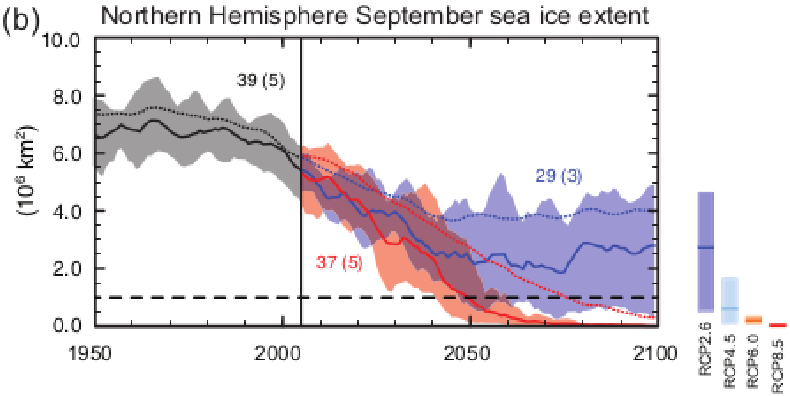


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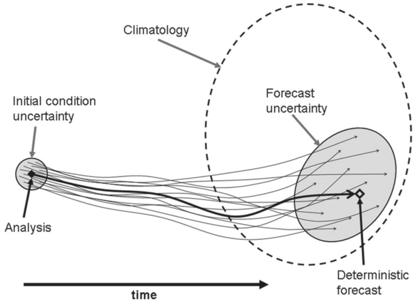
# Chaotic Nature of Natural Variability

(Lorenz, 1969; Griffies and Bryan, 1997, etc.)

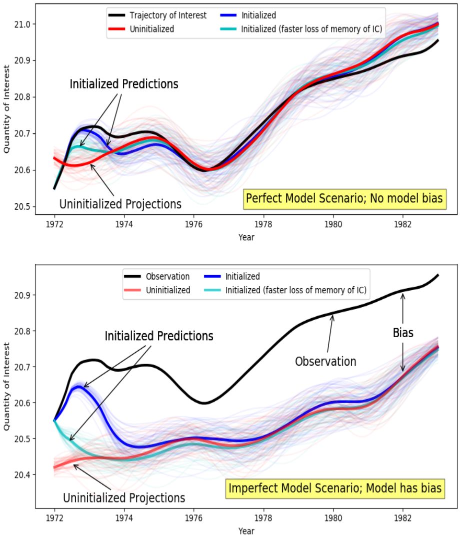
- Conduct initial condition ensemble simulations with climate model
- Obtain forecast dist. $P(\mathbf{v}|\boldsymbol{\theta})$ ($\boldsymbol{\theta}$ is obs.) and climatological dist. $P(\mathbf{v})$)




(Swinbank et al. (2016) Cambridge University Press)

- Conduct analysis of forecast error covariance $\Sigma_F$ and climatological covariance $\Sigma_C$ (assuming normal dist.)
  - Canonical Correlation Analysis
  - Discriminant Analysis
  - Predictive Component Analysis

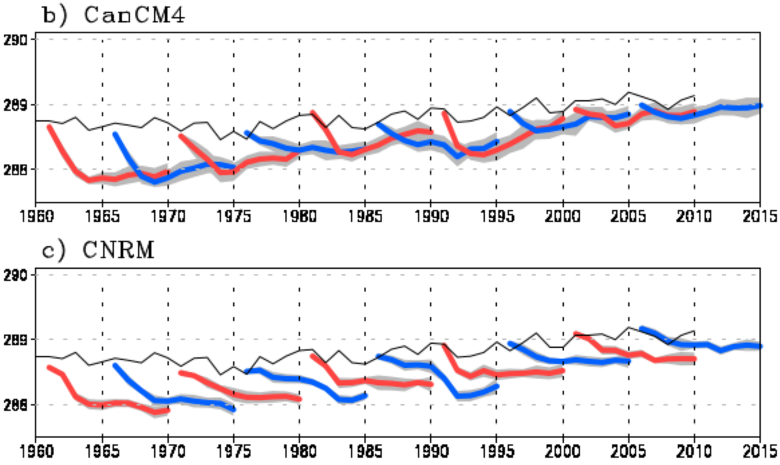
# Difficulty with Predicting Natural Variability: Model Bias




- Predictability studies are conducted in perfect model settings
- However all climate models are imperfect (have biases)
  - Extremely difficult to model the exact balance (small residual) of myriad (large) processes that lead to the mean state of the climate system and modes of variability
  - Small difference between large numbers

# Initialized Predictions of Various QoIs in Various Models Display a Jump Behavior

## Surface Temperature in CanCM4 and CNRM




(From Kim et al., 2012)

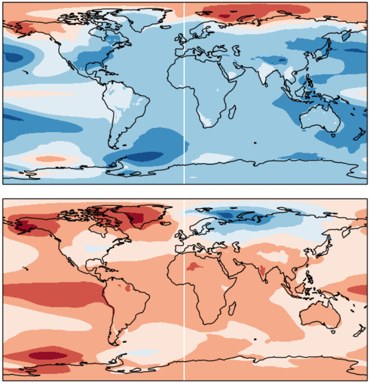
# Outline

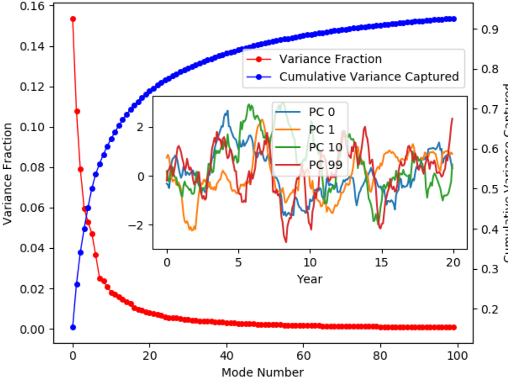
# What are the predictability characteristics of the spatiotemporal variability of surface temperature

- State of the art IPCC class model: NCAR CESM2
- Seasonal cycle removed
- Formulate problem with different forms/complexity, model order reduction, data augmentation, ...
- Develop learning based prediction system with different architectures
- Analyze predictability

# Modeling in Spatial Domain

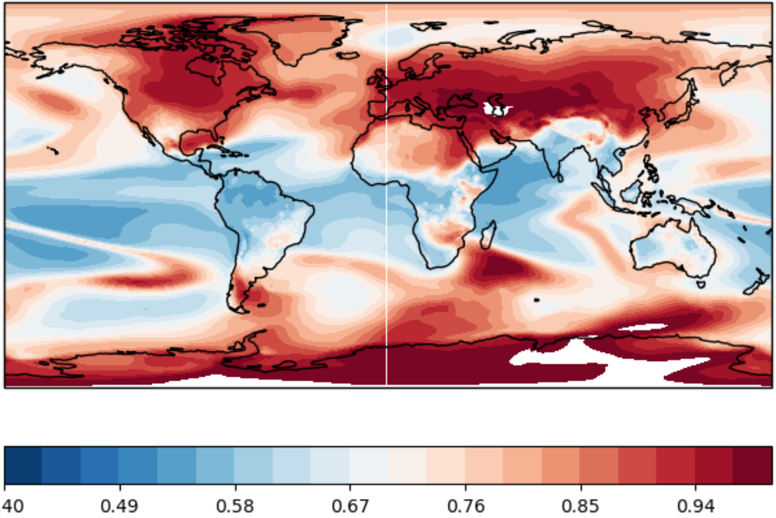
## PCA is used for model order reduction in some cases






First two EOFs (left) of the interannual variability of global surface temperature. Variance fractions, cumulative variance explained, and evolution of the prinicipal components over a short 20 year period are shown on the right

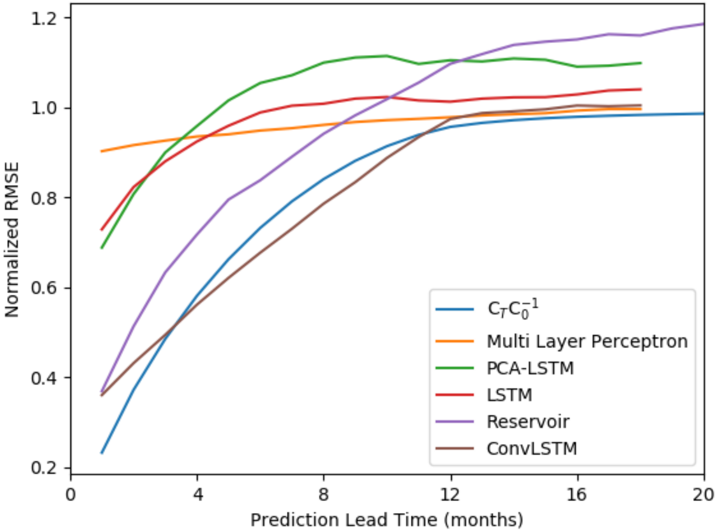
# Prediction Error Map




Errors greater at mid and high latitudes

Errors greater over land

# Comparison of Predictive Skill Across DNN Architectures and Other Statistical/Dyn. Models (No Climate Models)



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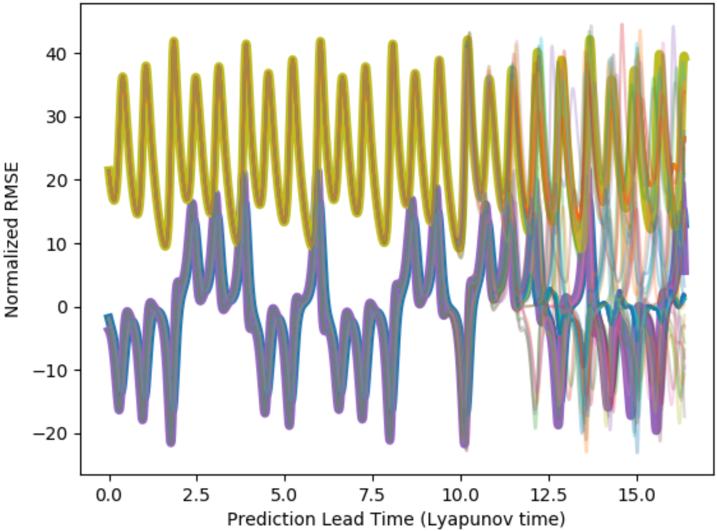
# When presented with the full system, the neural network can learn the Lorenz '63 attractor



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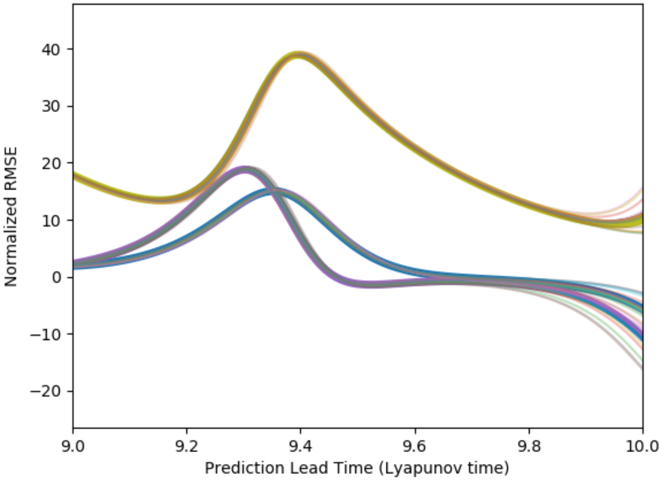
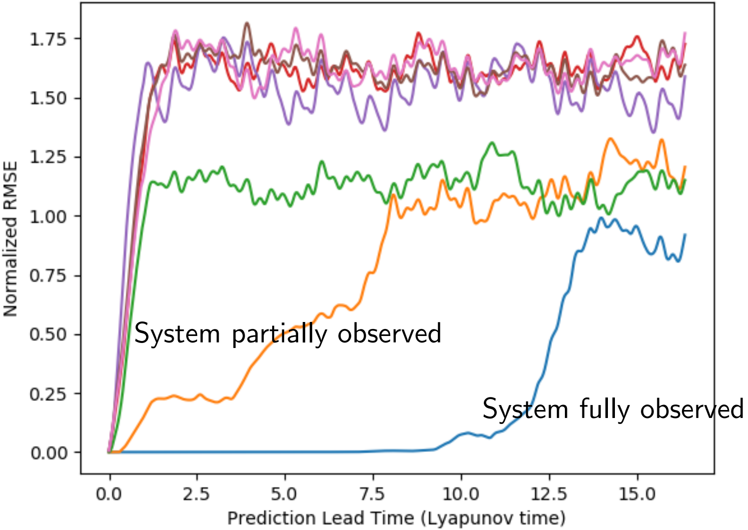


# However, not so when the system is only partially observed



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# Summary and Future Work

(Ongoing work)

- Predictability studies conducted in perfect model settings suggest that predictability extends to the decadal timescale
- In reality, however predictive skill vanishes much much faster. Model bias is one reason
- What do data driven methods have to offer in this setting?
- Learning based prediction system developed for an Earth System Model
- The system and the predictions need to be analyzed to identify predictable patterns and establish predictability
- Transfer methodology to observations