Boreal Wildfires and Climate Feedbacks: Towards a Satellite Informed AI Wildfire Digital Twin to infer Climate Change

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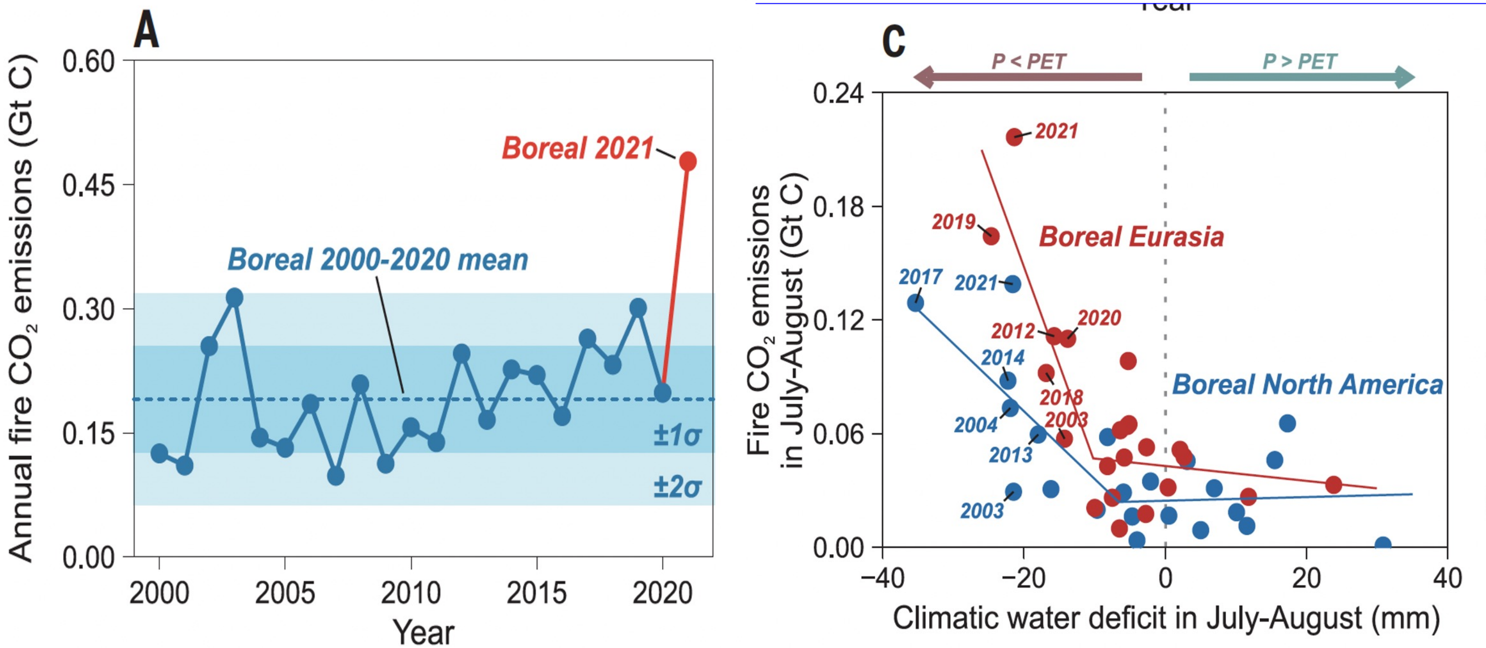
Record-high CO_2 emissions from Boreal Fires in 2021
B. Zhang et. al., Science 3 March 2023



Taken From B. Zhang et. al., Science 3 March 2023

Boreal Wildfire CO_2 emissions in 2021 are 25% of global net CO_2 emissions.
The Arctic is warming two times faster than the rest of the planet—
The Boreal region has warmed 2°C above pre-industrial levels, while Earth warmed 1.1^{0}C.
Are Boreal wildfires having a positive feedback on climate change?
Are CO_2 emissions from Boreal Forest Mega-wildfires trending to a climate tipping point?

"A tipping point is the point at which small changes become significant enough to cause a larger, more critical change that can be abrupt, irreversible, and lead to cascading effects.
A "Tipping element'' is used to describe large-scale components of the Earth system that may pass a tipping point. Lenton et.al., 2011. Wildfires low on list of climate tipping elements

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Boreal Forests

World's largest land-based biome The forest biome. *UC Berkeley*

Taiga

- Boreal forests cover 16.6 million km^2 ; the Amazon forest is 9.9M sq kms.
- Arctic boreal heating is undergoing most rapid change on planet since pre-industrial era.(2^0 vs 1.1^0)
- Boreal wildfires can accelerate permafrost thaw, expose stored carbon to decompose by soil microbes.
- This is gradual but fires can contribute to a nonlinear, abrupt thaw with greater consequences.

Wildfire/Climate Feedbacks

- Climate change affects global wildfires by increasing the fire season, the size of areas affected by fire. In addition, droughts and extreme local temperatures are exacerbated by climate change and make wildfires more likely.
- Climate change causes winters to become shorter and weather becomes drier and windier, leading to more intense fires occurring across larger areas.
- Savannahs and crops replace burned areas with higher albedos (solar reflectance) increasing surface warming and droughts. (Charney et. al., Effects of Albedo Change on Droughts, 1977)
- Forests absorb 30% of the net CO_2 emitted to the atmosphere. Boreal Forests fires emitted ~ 10% of net CO_2 emissions yearly from 2000-2020. In 2021, B. Zheng et. al., measured ~24% net CO_2 emissions.
- Amazon facing 2 climate tipping points when 4^0 C change or 40% deforestation, (C. Nobre et. al., 1990, 2007, 2016, 2022). Deforestation in Amazon has been near constant past 5 years.
- Boreal fires have been increasing at rate of ~6%/year over the past 15years almost doubling mean CO_2 emissions.
- 'What if' Boreal forest fires regularly emitted ~25% of net CO_2 emissions and burnt ~25% of forest areas.

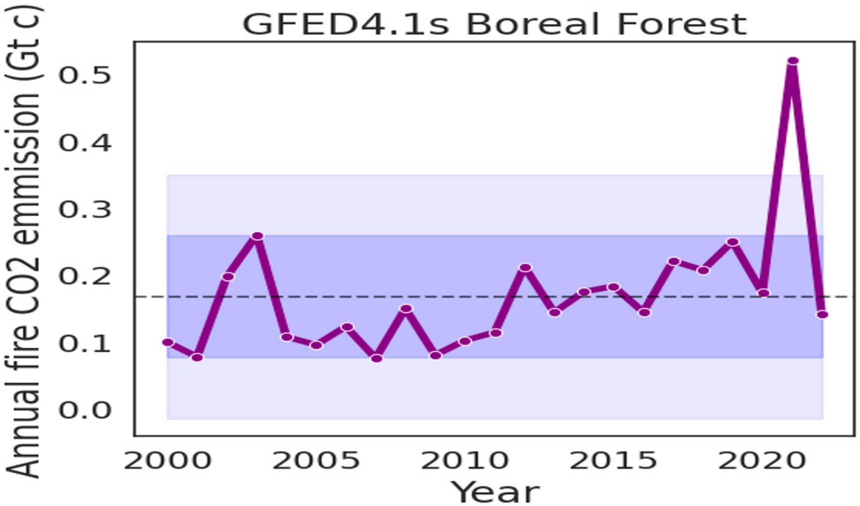
Can satellite informed AI based Boreal Wildfire Digital Twins provide reliable early warnings of a Boreal biome tipping point?

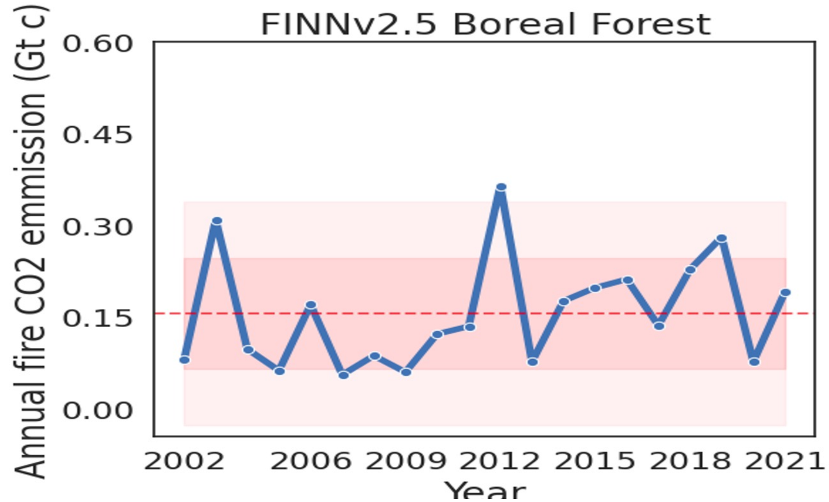
AI/ML Wildfire Digital Twin Forecasts for 2021 and beyond...

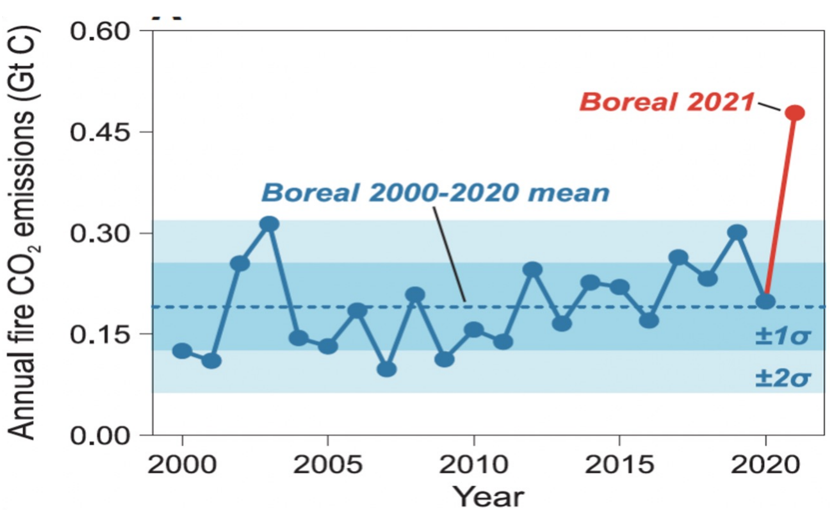
The following are preliminary results from Works-in-Progress:

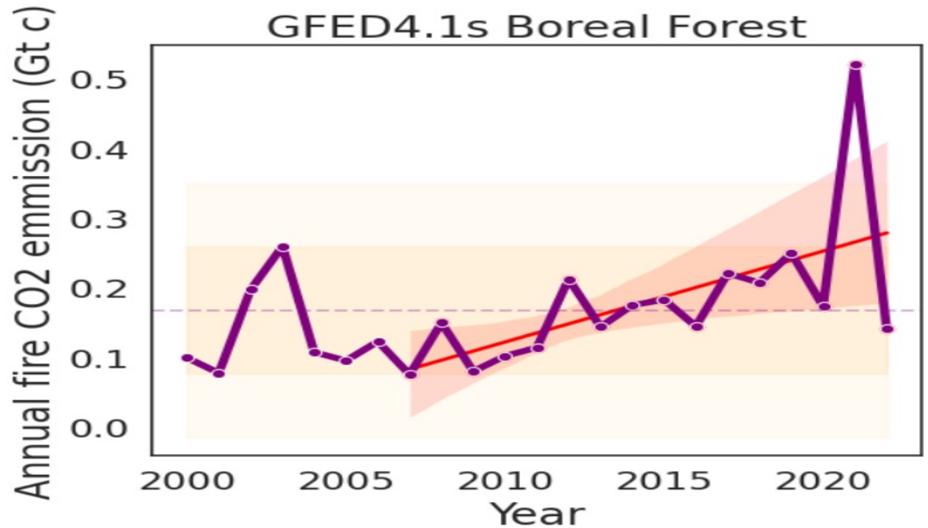
- Employing 5 distinct monthly Boreal Wildfire CO2 emission data sets;
  - GFEDv4.1s MODIS & VIIRS (ORNL/DAAC)
  - FINN 2.5 MODIS & VIIRS, (NCAR)
  - MOPPIT v2 CO,
  - ERA5-Land & ERA5
- Implementing 3 AI/MI global models
  - **Wavelet Neural Operators** (IIT-2-D) -> 3-D + Attention
  - FourCastNet (Nvidia)
  - Resnet, etc.
  - UNet with SWIN Transformer (Pangu)?
- Conducting 3 dynamic physical global simulations.
  - CESM2-CMIP6, Shared Socioeconomic Pathways (SSP):
  - NUWRF/ SFire BONA-FINN v2.5,
  - NUWRF/CHEM/SFire BOAS-FINN v2.5,
  - Implementing Nvidia AI Digital Twin S/W on NCCS ADAPT

Need to explain why B. Zheng yearly data set is consistent with FINN2.5 and GFED 4.1s 2002 -2020 but differs in 2021 only with FINN2.5 and not GFED4.1s?









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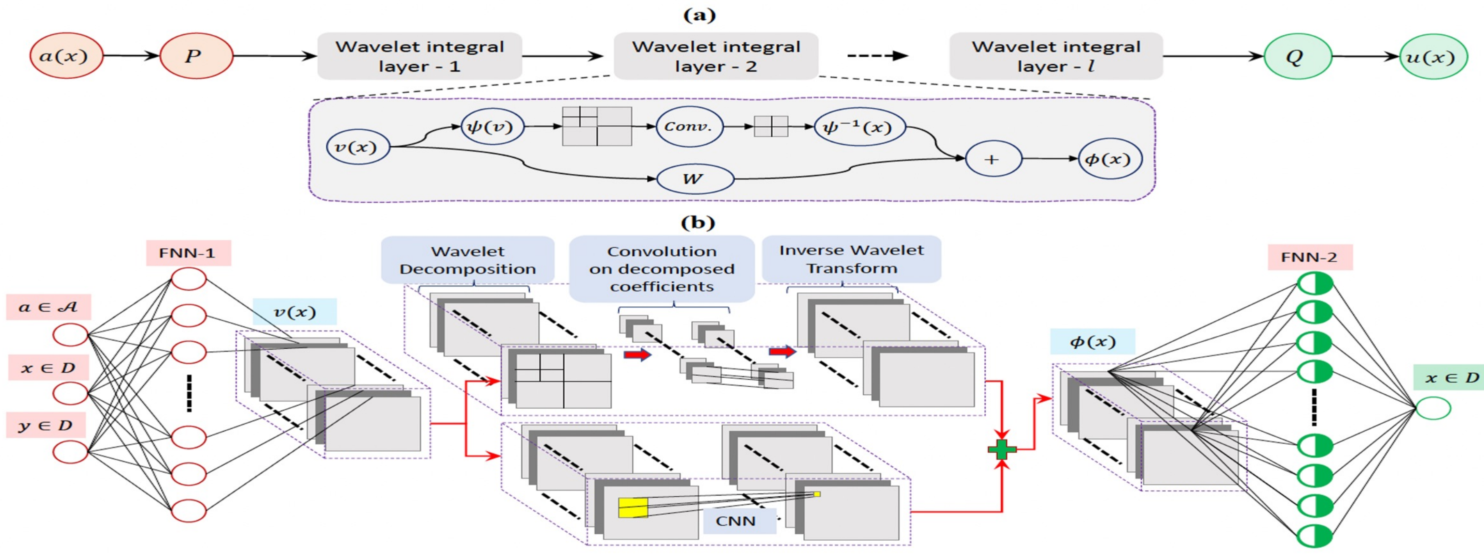
Wavelet Neural Operator Architecture

T. Tripura, S. Chakraborty, Sci.Direct 2023

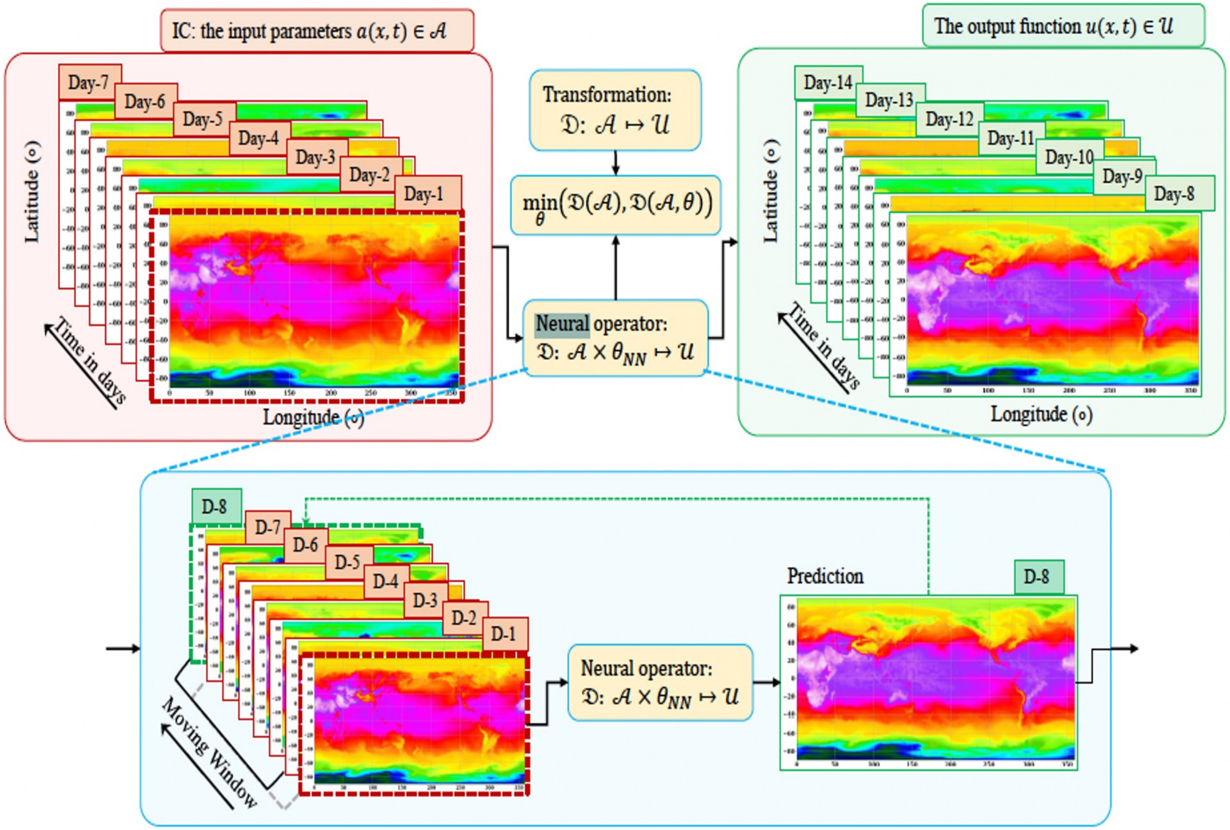


(a) Illustration of Wavelet Neural Operator (WNO) architecture. First lift the inputs to a higher dimension by a local transformation P( ). Then pass the lifted inputs to a series of wavelet kernel integral layer. Transform back the final output of the wavelet integral layer using a local transformation Q( ). Activation of output of Q( ) provides solution u(x).

(b) Example of WNO with one wavelet kernel integral layer. The inputs contain the initial parameters and space information. The local transformations P( ) and Q( ) are shallow fully connected neural networks. Output of P( ) is fed to the wavelet integral layer. The integral layer consists of two separate branches. (i) Performs wavelet decomposition of inputs followed by parameterization of integral kernel. (ii) A convolution neural network (CNN) with kernel size 12 is constructed. The outputs of the two branches are then summed and activations are performed. Then the outputs are passed through the transformation Q( ), which provides the target solution u(x). In similar manner, a WNO with arbitrary number of wavelet integral layers can be be constructed.

https://github.com/csccm-iitd/WNO

We test the Wavelet Neural Operator for Data Driven Image Mapping



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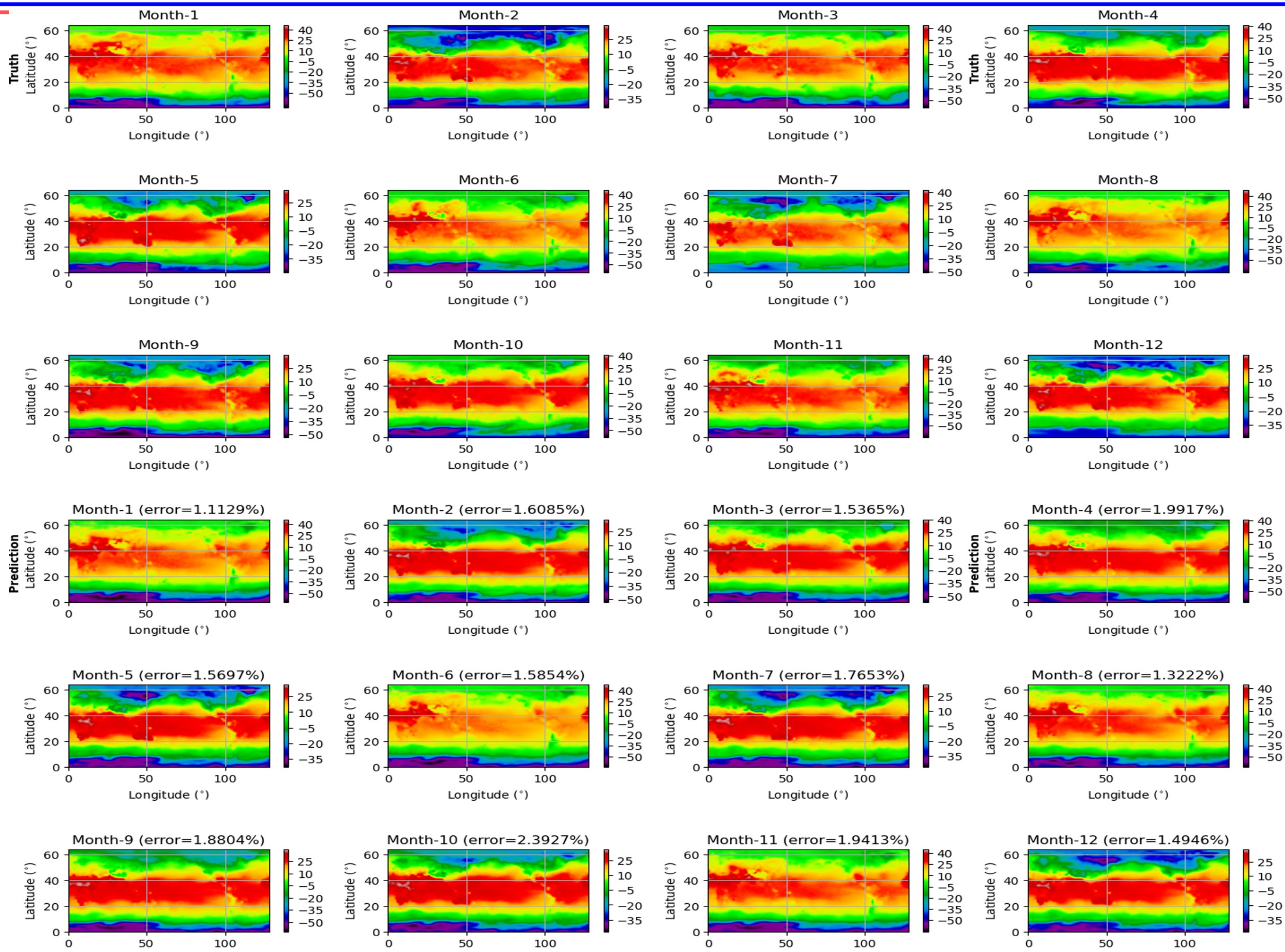
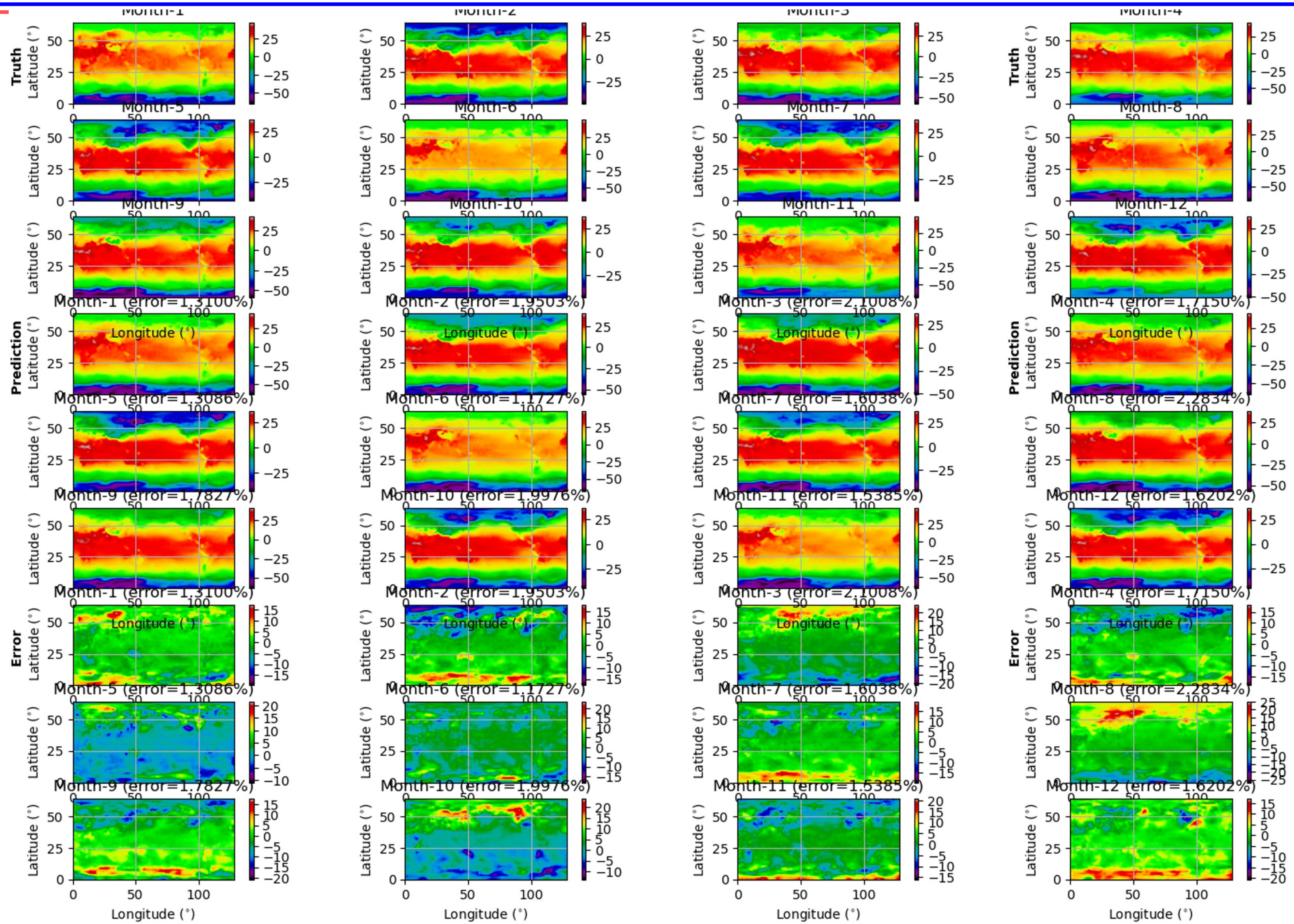
A Yearly Prediction of 2m Temperature



Yearly Persistence Forecast 2019 - 2020



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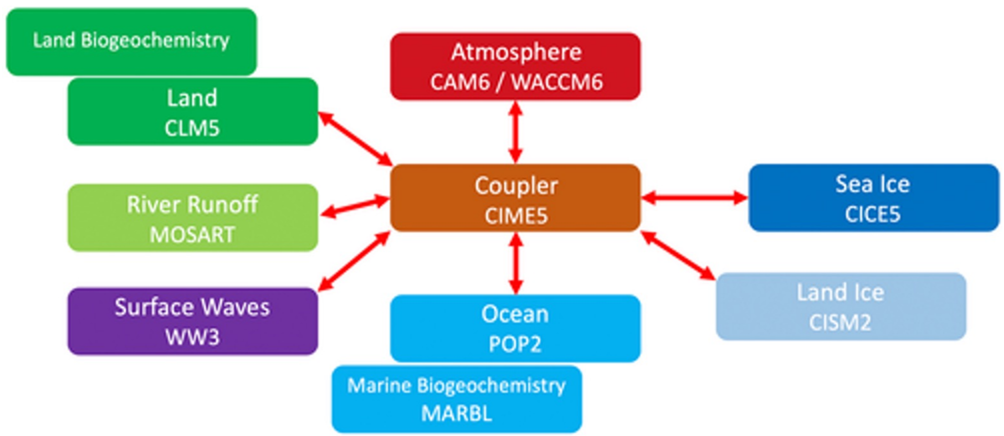
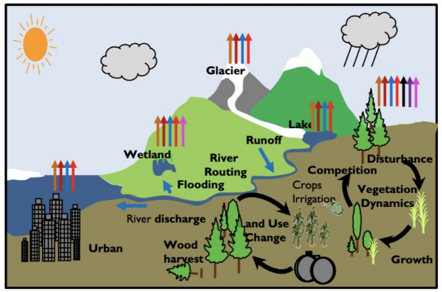
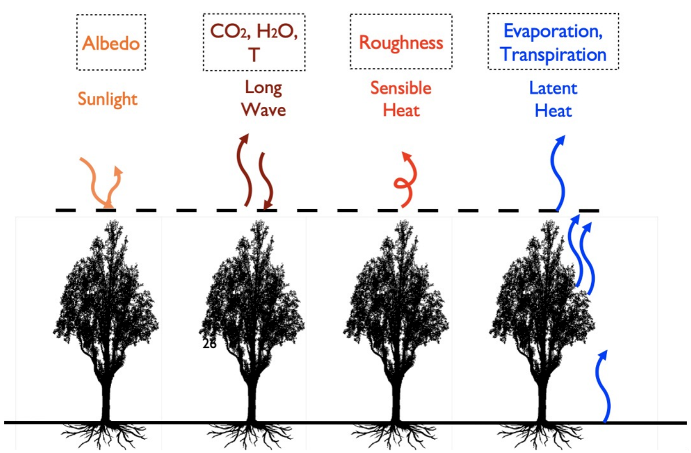
CESM2 Model Component Configuration



Land Modeling



Lawrence et al., 2019



Atmosphere
The Community Atmosphere Model Version 6 (CAM6) uses the Finite Volume (FV) dynamical core

Ocean
Parallel Ocean Program Version 2

Land
The Community Land Model Version 5 (CLM5)

CESM2 Model Simulations

Two monthly CESM2 runs started for 4 years each with the latest model configuration to understand the climate feedback/ tipping points:

1. Performing sensitivity experiments with CESM 2 (some of the set ups already use satellite phenology for land model initialization)
2. We use SSP experimental setup for future projections
3. Can study similar processes in both low and high-resolution runs.

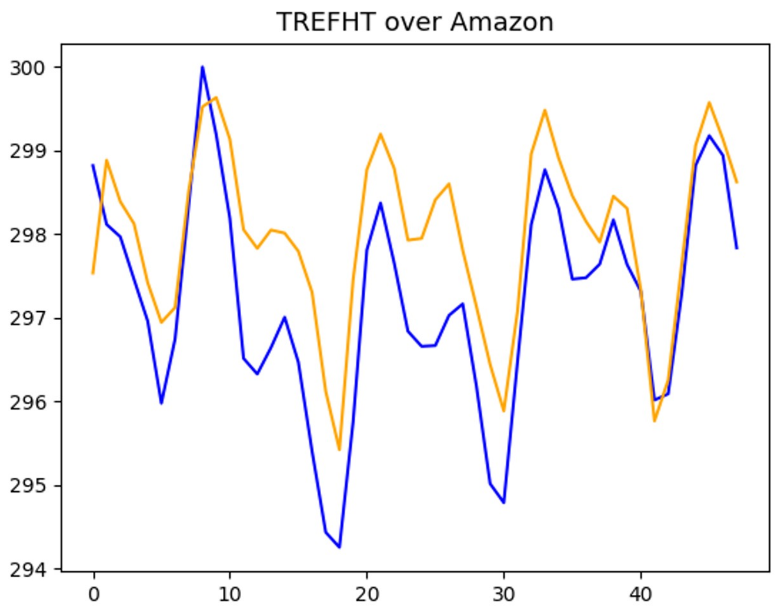
The SSPs (Shared Socioeconomic Pathways) describe alternative evolutions of the future society in the absence of climate change or climate policy.

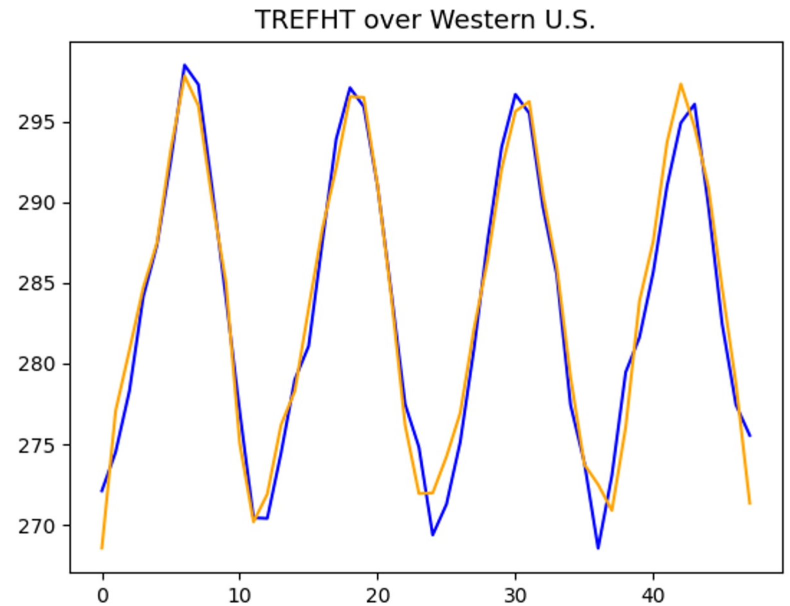
SSPs 1 and 5 envision relatively optimistic trends for human development, with substantial investments in education and health, rapid economic growth, and well-functioning institutions.

SSPs 3 and 4 envision more pessimistic development trends, with little investment in education or health, a fast-growing population, and increasing inequalities.

CESM2 includes

NTCFs; namely tropospheric aerosols, tropospheric O3 precursors, and CH_4





AMAZON Forest Area
West Coast of USA

Control Run

Cmip6 forcing

2m Air Temp

Fully active components

Summary

- **Boreal Wildfire Emission Emergency**
  - Carbon dioxide emissions from boreal forest fires have been increasing since at least the year 2000, reaching a new high in 2021, Zheng *et al*. report. ...... The increasing number of extreme wildfires that is accompanying global warming presents a real challenge to global climate change mitigation efforts. —HJS

    (H.J.S. is a Senior James Martin Fellow at Oxford University.)

  - Earth future climate might or might not have a domino like succession of tipping points that turns the system into a hothouse after an uncertain number of centuries. Sea level rise of 70m and extremes of surface storminess lieing well outside of human experience. Such worst-case scenarios are highly speculative. But they cannot be ruled out with complete confidence in the present state of climate science and climate modeling.

    --Michael McIntyre is Professor Emeritus U Cambridge UK and Fellow Royal Society

Thank You

For more questions contact: halem@umbc.edu

5 level Wavelet 2-D Decomposition

Proposed Algorithm (Input: Image I from the dataset)
(1) Read image (I) as $LL0$
(2) for i = 1 to 5
(3) (LLi, LHi, HLi, HHi) = two-dimensional wavelet decomp($LL(i$–1)).
(4) Hi = Histogram (LLi)
(5) Obtain concatenated histogram of size 256 Å~ 5, H by concatenating five histograms ($H1$, $H2$, $H3$, $H4$ and $H5$) obtained in Step (4).
(6) Compute feature vector fi (of size 256 Å~ 1) = Probabilistic principal component analysis (H, 1)
(7) Input the feature vector fi as obtained in step (6) into a KNN or ANN model for classification of images.

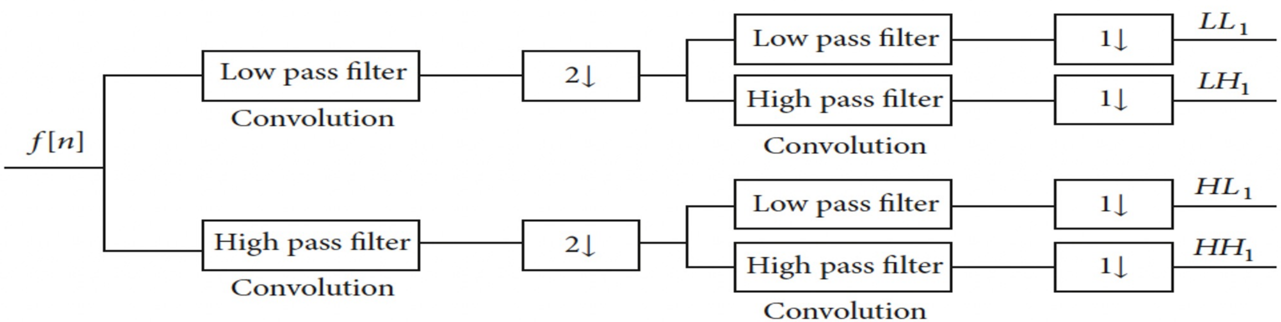


FIGURE 1: Extraction of 2D DWT components.

$$h = \left\{ \frac{\sqrt{3}+1}{4*\sqrt{2}}, \frac{3+\sqrt{(3)}}{4*\sqrt{(2)}}, \frac{\sqrt{3}-1}{4*\sqrt{2}}, \frac{3-\sqrt{(3)}}{4*\sqrt{(2)}} \right\},$$

$$g = \left\{ -\frac{3+\sqrt{(3)}}{4*\sqrt{(2)}}, -\frac{\sqrt{3}-1}{4*\sqrt{2}}, \frac{3+\sqrt{(3)}}{4*\sqrt{(2)}}, -\frac{\sqrt{3}+1}{4*\sqrt{2}} \right\}.$$

Daubechies -4 wavelet high and low pass filters

Srivistava tt.al.Hinawi,2017

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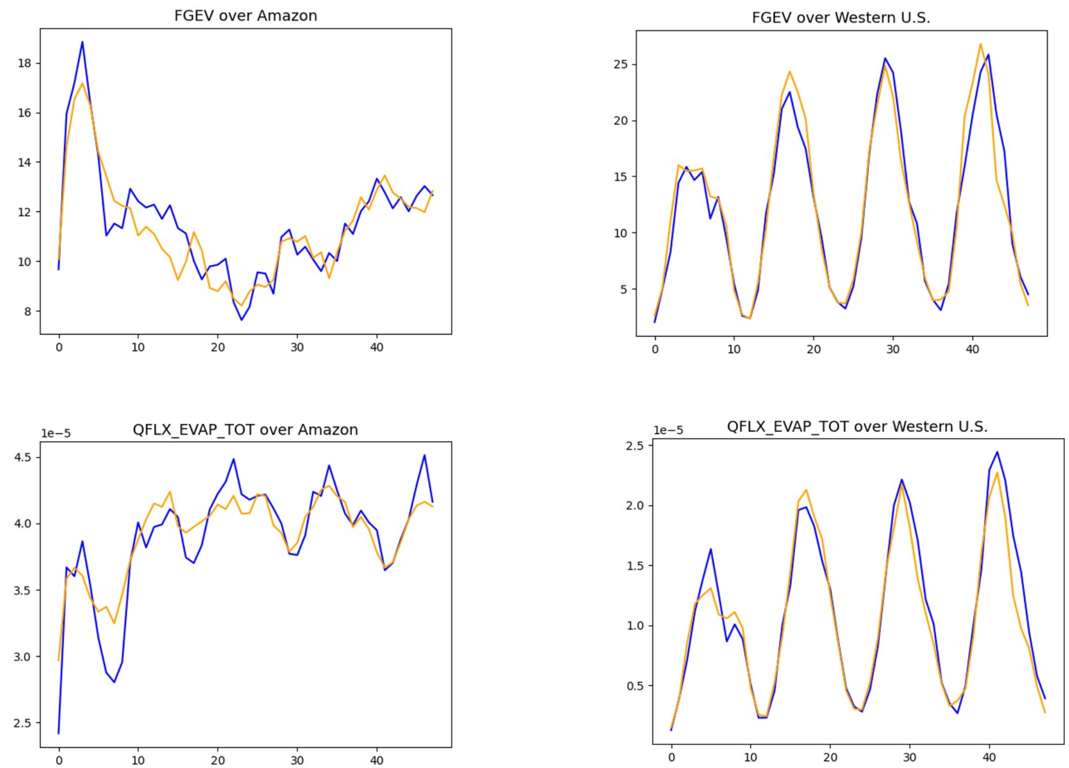
AMAZON Forest Area
West Coast of USA

~Evapotranspiration

Preliminary analysis:

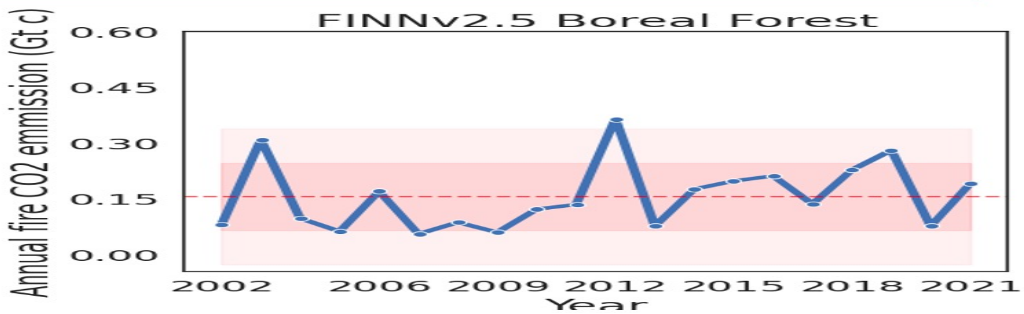


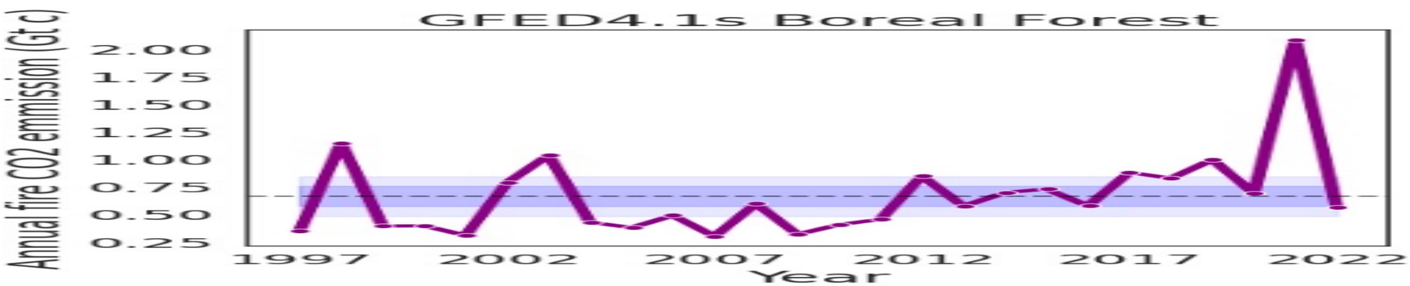
Control Run

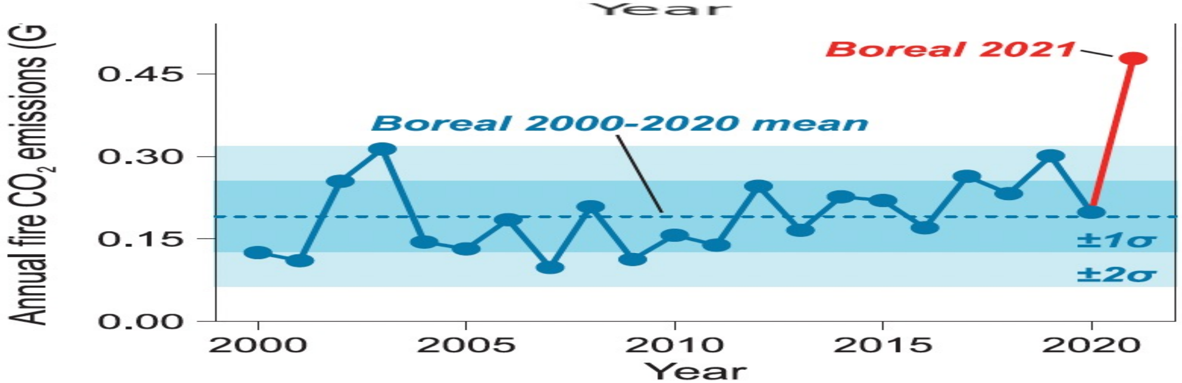
Cmip6 forcing

Fully active components

Why does the B. Zheng yearly data set differ from yearly FINN and GFED 4.1s data.







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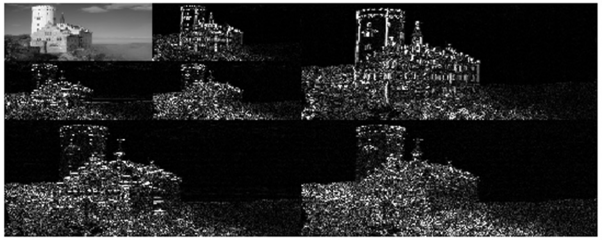
Wavelet Decomposition

WIKIPEDIA
The Free Encyclopedia

Wavelet transform

In mathematics, a **wavelet series** is a representation of a square-integrable (real or complex-valued) function by a certain orthonormal series generated by a wavelet. This article provides a formal, mathematical definition of an **orthonormal wavelet** and of the **integral wavelet transform**.[1][2][3][4][5]



An example of the 2D discrete wavelet transform that is used in JPEG2000.

Definition

A function $\psi \in L^2(\mathbb{R})$ is called an **orthonormal wavelet** if it can be used to define a Hilbert basis, that is a complete orthonormal system, for the Hilbert space $L^2(\mathbb{R})$ of square integrable functions.

The Hilbert basis is constructed as the family of functions $\{\psi_{jk} : j, k \in \mathbb{Z}\}$ by means of dyadic translations and dilations of ψ,

$$\psi_{jk}(x) = 2^{\frac{j}{2}} \psi(2^j x - k)$$

for integers $j, k \in \mathbb{Z}$.

If under the standard inner product on $L^2(\mathbb{R})$,

$$\langle f, g \rangle = \int_{-\infty}^{\infty} f(x)\overline{g(x)}dx$$

this family is orthonormal, it is an orthonormal system:

$$\langle \psi_{jk}, \psi_{lm} \rangle = \int_{-\infty}^{\infty} \psi_{jk}(x)\overline{\psi_{lm}(x)}dx$$
$$= \delta_{jl}\delta_{km}$$

where δ_{jl} is the Kronecker delta.

Completeness is satisfied if every function $f \in L^2(\mathbb{R})$ may be expanded in the basis as

$$f(x) = \sum_{j,k=-\infty}^{\infty} c_{jk}\psi_{jk}(x)$$

with convergence of the series understood to be convergence in norm. Such a representation of f is known as a **wavelet series**. This implies that an orthonormal wavelet is self-dual.

The **integral wavelet transform** is the integral transform defined as

$$[W_\psi f](a, b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} \overline{\psi\left(\frac{x-b}{a}\right)} f(x)dx$$

The **wavelet coefficients** c_{jk} are then given by

$$c_{jk} = [W_\psi f](2^{-j}, k2^{-j})$$

Here, $a = 2^{-j}$ is called the **binary dilation** or **dyadic dilation**, and $b = k2^{-j}$ is the **binary** or **dyadic position**.

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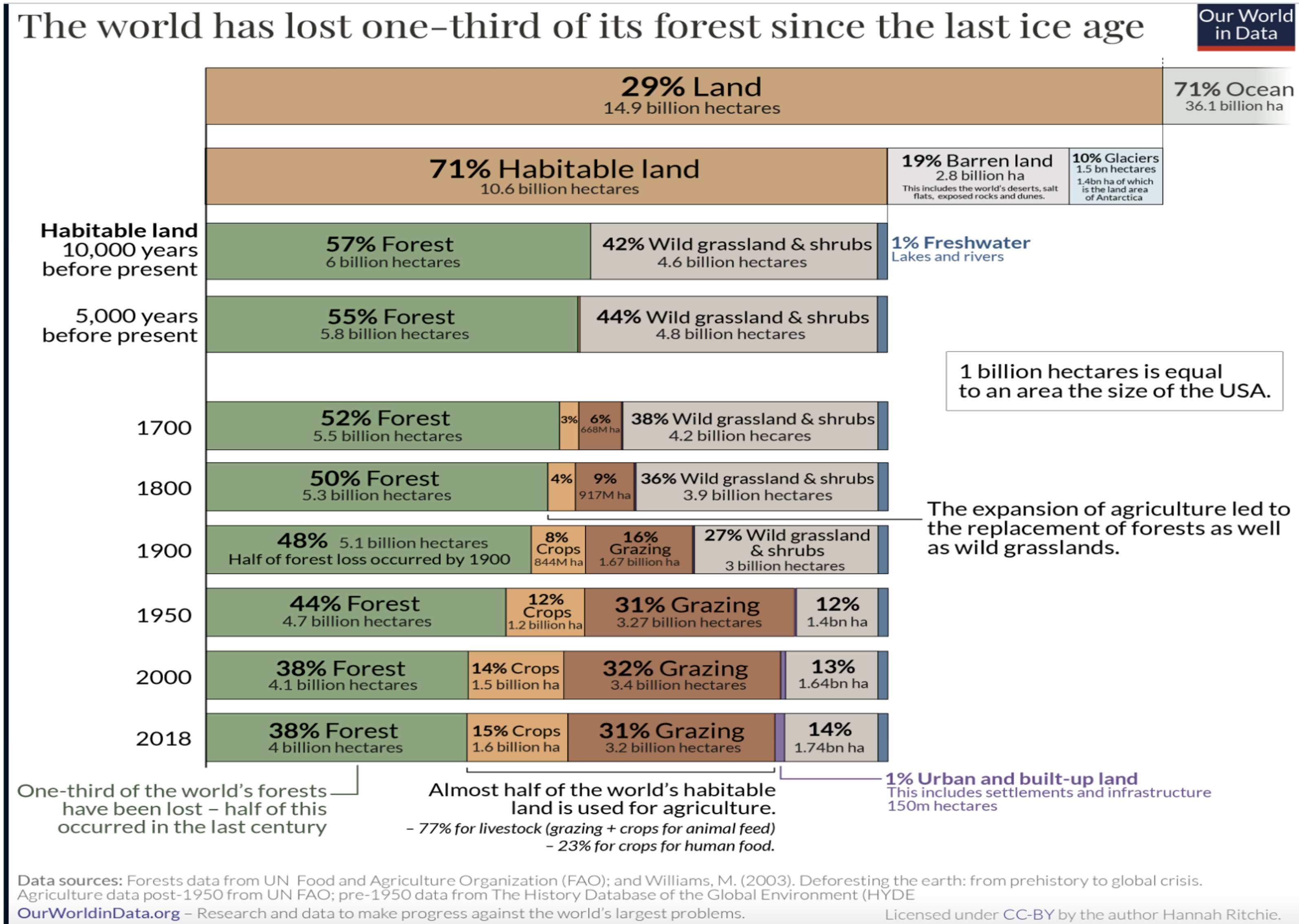
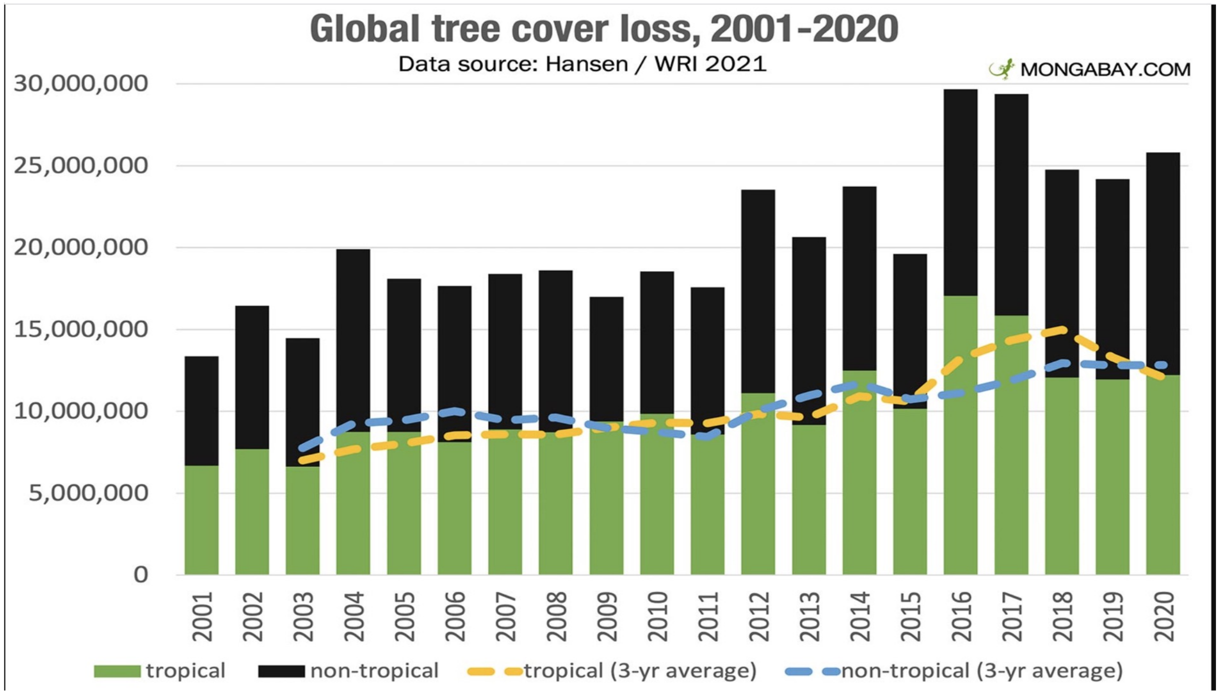
Global Forest Loss



Growth of Non-Tropical Deforestation



Hectares loss due to wildfires for the tropics and extra tropics in the 21 century.

2001 -2020 Tropical 7M – 13M, Non Tropical 7M – 14M Total Loss 14M Hectares (38 M Acres)
Global CO2 from fires is ~2 GTgC/yr. (GFED4.1s)
Global CO2 from fossil fuels and land use change is ~11GTgC/yr.

(Hansen, 2021 UMD)

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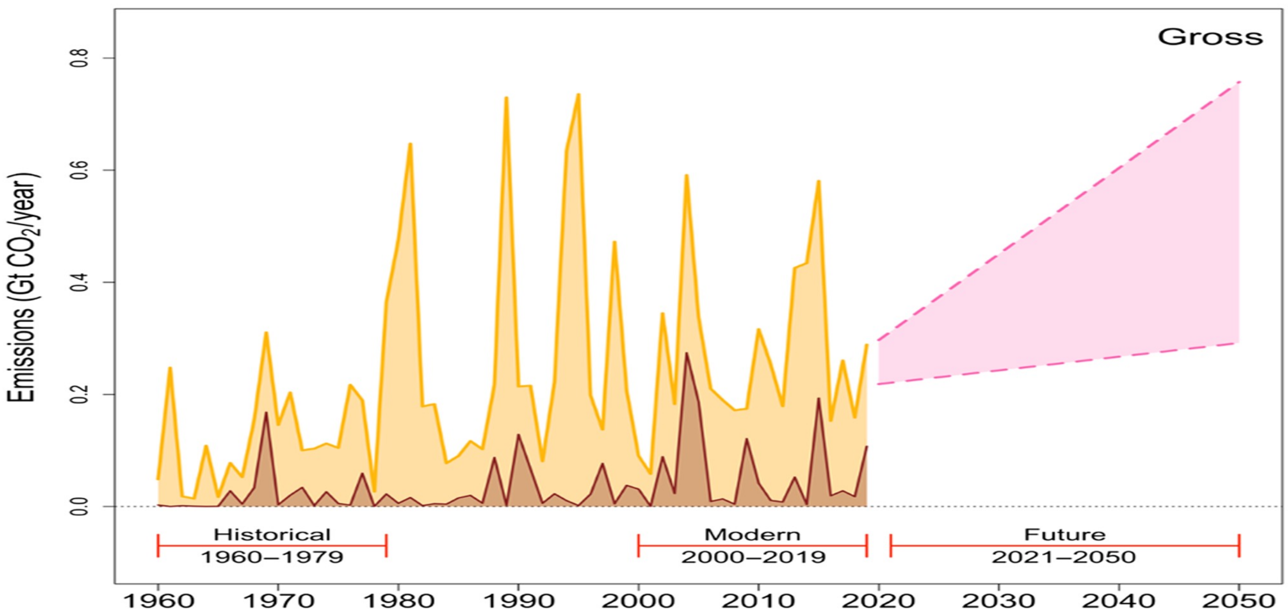
Some Boreal Forest Facts

Boreal forests cover ~16.6 M km^2 across the circumpolar region; Amazon 9.9 M km^2

BF contains approximately two-thirds of global forest carbon.

Boreal wildfires are accelerating the release of carbon stored in these ecosystems.

Boreal biome temperatures rising at twice the global average rate (2^{0}C vs 1.1^{0}C)



Observed (1960–2019) and Projected (2020–2050) gross emissions from boreal North America.
Dark brown Alaska and light brown Canada. Linear est. 0.5+/-0.2 Gt CO2/yr

Phillips et. al., Sci. Adv. 8 (2022)

Mitigating AI/ML challenges in predicting tipping points

- Predicting a tipping point of a single time series (CO2) based solely on prior observations with AI/ML models or statistical and/or physical based models is a daunting challenge, if not impossible, without additional information such as physical or chemical inferred constraints.

- We assume access to multiple observational global yearly data sets from satellite data systems, one of which includes an outlier > 3 sigma std. deviation implying a potential transition point.

- Data from satellites have been shown to model fire spread comparable to dynamic parametrizations . (Lassman et.al., 2023)

- We employ a dynamical physical ensembles model to generate simulated time series forced by the alternative observational systems for predicting the transition point and beyond.

- ***We present preliminary test results of a unique data driven sequential approach to conducting Machine Learning Simulated Climate Predictions over multiple years or decades.***

- ***We plan to apply a physics informed coupled system to using AI yearly forecasts with backward propagation with derived CESM2 variables to constrain the AI model predictions.***

- We deal with the trustworthiness of AI/ML models and physical observations by implementing multiple ML genres trained with multiple sources of observational data sets.

Regression fit from 2007