CCAI Summer School 2023

Tackling Climate Change with Machine Learning

Priya L. Donti, David Rolnick, Lynn H. Kaack

Climate change warrants rapid action


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Impacts felt globally

Disproportionate impacts on most disadvantaged populations

Need net-zero greenhouse gas emissions by 2050 (IPCC 2018)

- Across energy, transport, buildings, industry, agriculture, forestry, etc.

How does ML fit into this picture?

Lecture outline

Introduction to climate change

Opportunities for ML in climate action

Considerations for research and deployment

Is ML a help or hindrance for climate action?

Takeaways and how to get involved

Lecture outline

Introduction to climate change

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State of
climate change

Approaches for
climate action

The state of climate change

Earth has already warmed over 1°C, compared to pre-industrial period

Due to excess greenhouse gas (GHG) emissions from human activities

- E.g., carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O)

Has induced major changes in climate

- Climate = “average weather”
- Extreme heatwaves, precipitation, droughts, hurricanes, etc.

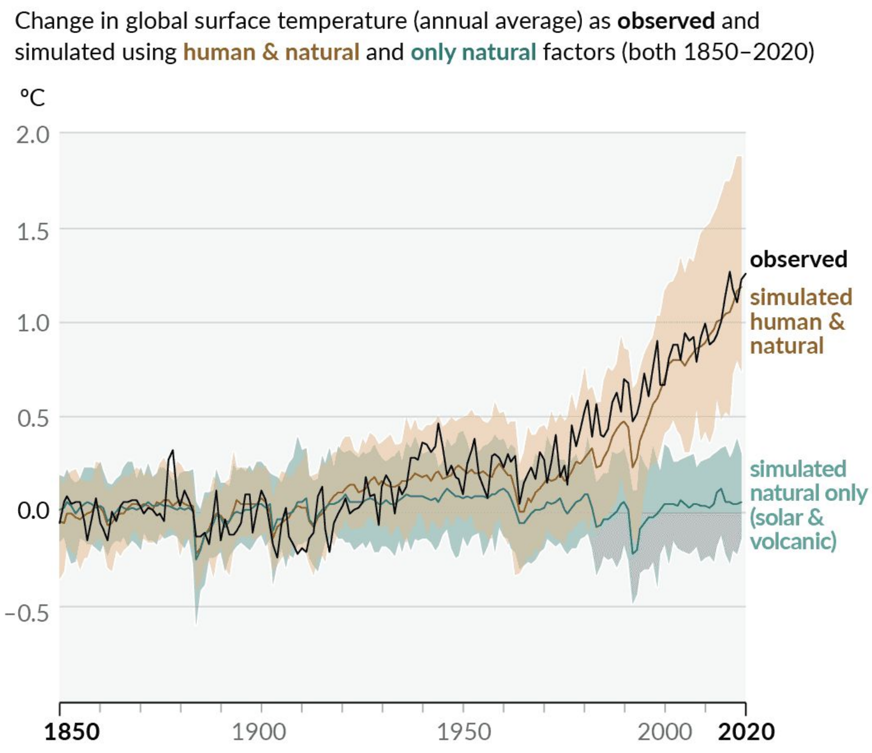
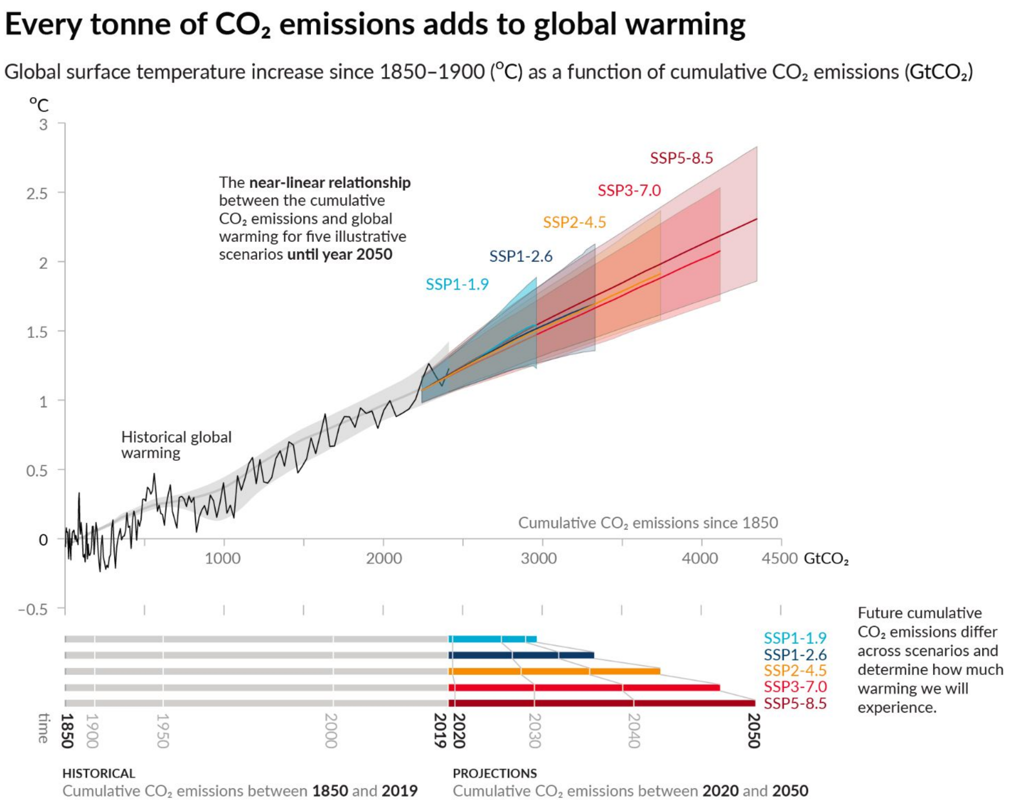


Figure source: IPCC AR6 WG1 Report (2021)

Rapid action is needed to limit warming



Speed and scale of systemic changes affects total warming

Net-zero by 2050 (**SSP1-1.9**) limits warming to ~1.5°C

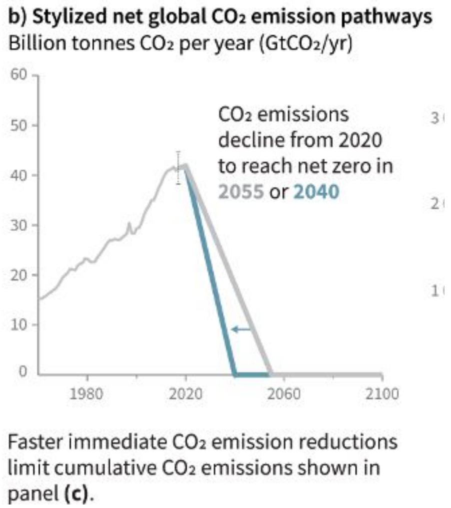


Figure source: IPCC AR6 WG1 Report (2021), IPCC Special Report (2018)

Approaches to addressing climate change

Axes of action

- **Climate science:** Understanding and predicting climate change
- **Mitigation:** Reducing or preventing greenhouse gas emissions
- **Adaptation:** Responding to the effects of a changing climate

Important frameworks

- **Climate justice:** An equity-centered approach to climate change
- **Co-benefits:** Explicitly considering linkages between climate action and other UN Sustainable Development Goals (SDGs)

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Climate change mitigation

Mitigation: Reducing or preventing GHG emissions

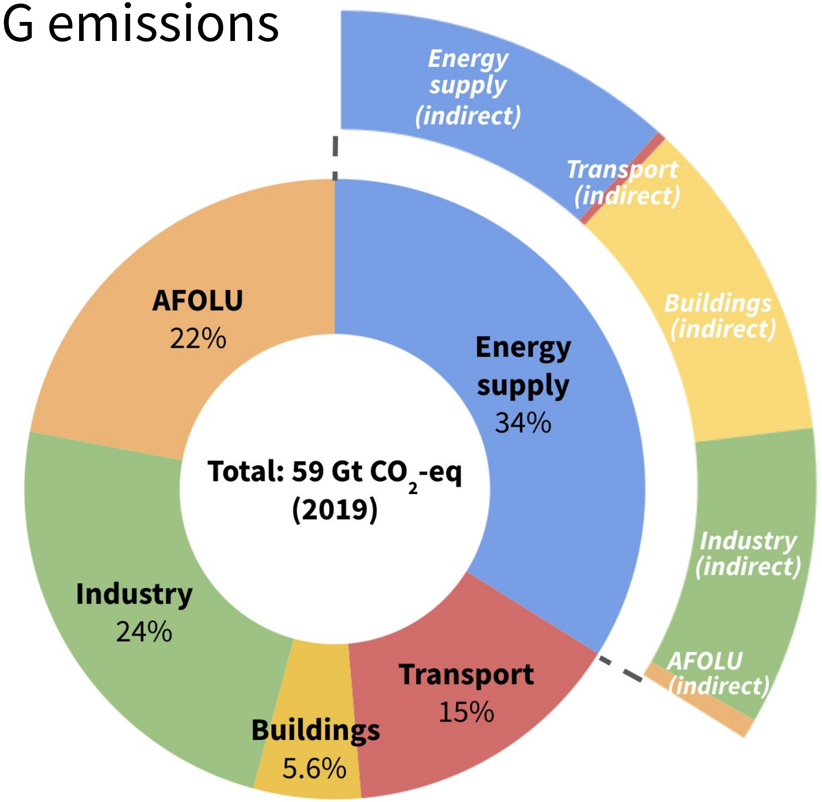


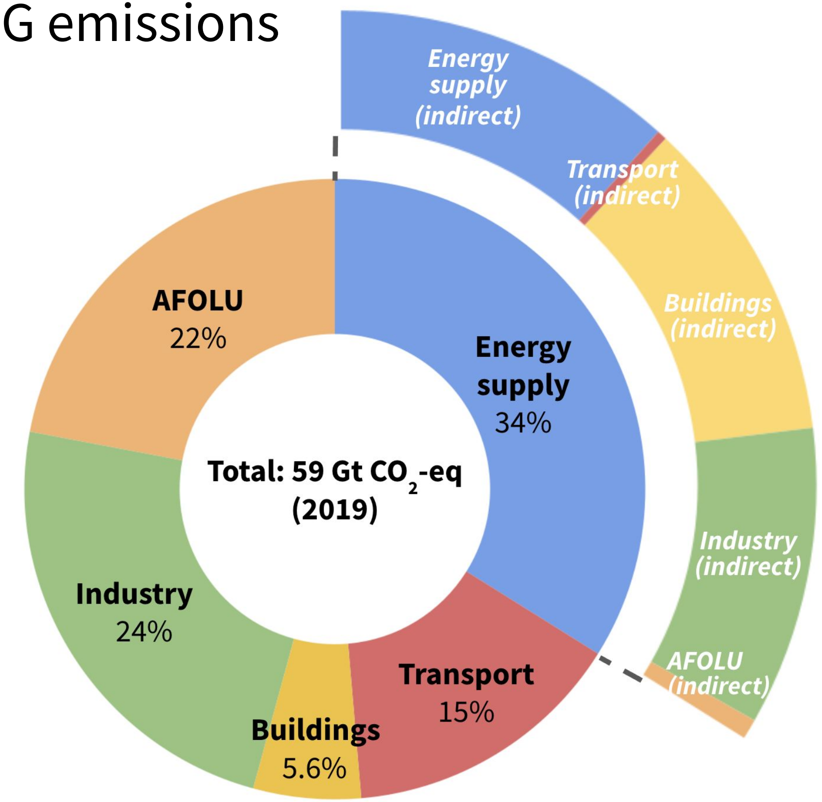
Figure data based on IPCC AR6 WG3 Report (2022). Percentages shown do not add to exactly 100% due to rounding to two significant figures.

Climate change mitigation

Mitigation: Reducing or preventing GHG emissions

Sectors

Energy supply
Transportation
Buildings
Industry
Agriculture
Forestry
Other land use
CO_2 removal



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Climate change mitigation

Mitigation: Reducing or preventing GHG emissions

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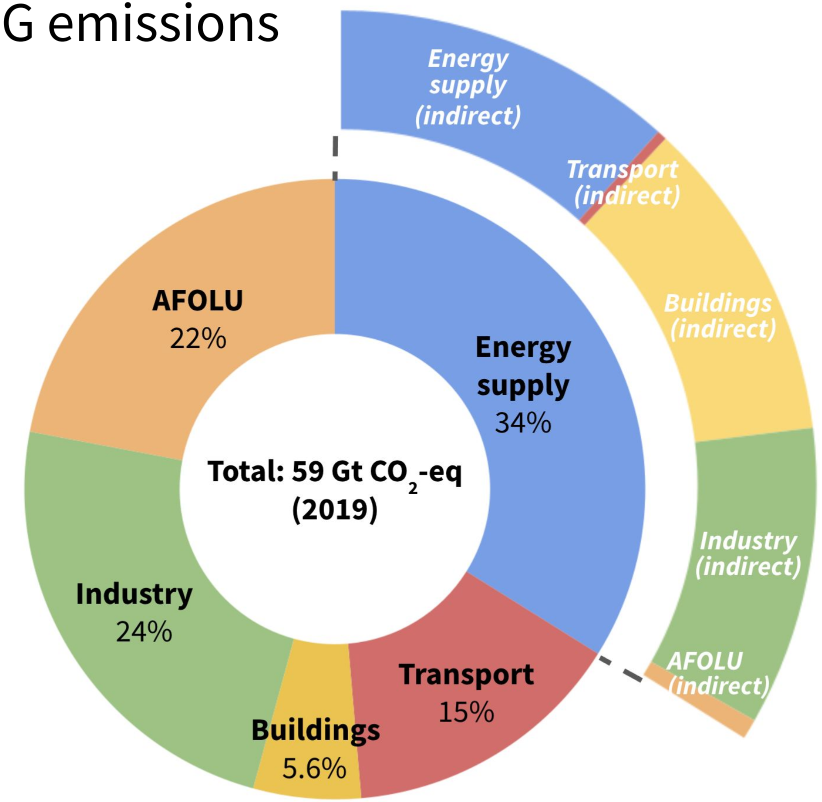
Energy-related emissions



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Climate change mitigation

Mitigation: Reducing or preventing GHG emissions

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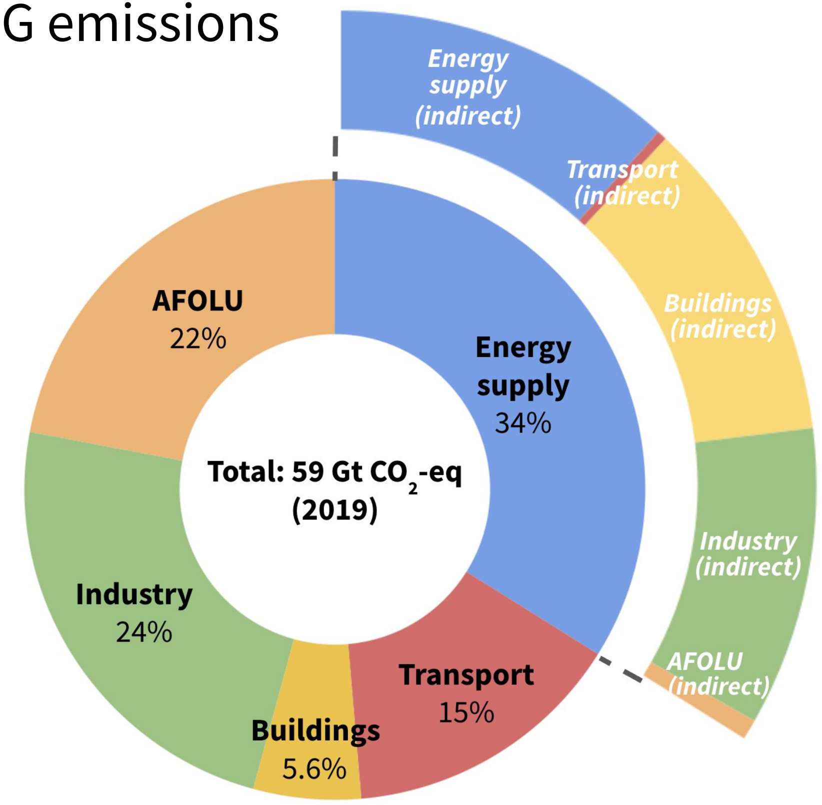
Land use (AFOLU) emissions



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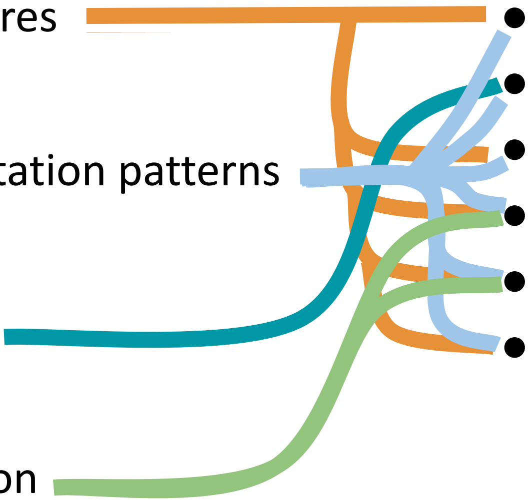
Climate impacts and downstream effects

Climate impacts

- Rising temperatures
- Changing precipitation patterns
- Rising sea levels
- Ocean acidification



Downstream effects

- Droughts and heatwaves
- More intense storms and flooding
- More frequent wildfires
- Loss of ecosystem services
- Biodiversity loss
- Spread of disease vectors and pests

Figure adapted from Kris Sankaran

Climate change adaptation

Adaptation: Responding to the effects of a changing climate

Climate change adaptation

Adaptation: Responding to the effects of a changing climate

1. Measuring and predicting risks
    - **Risk**: Impact x probability

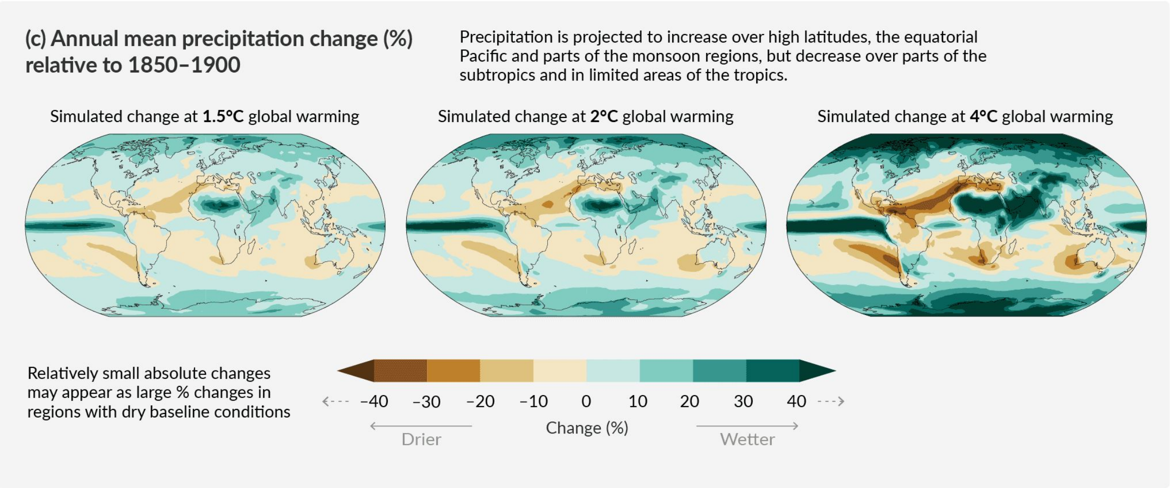


Figure source: IPCC AR6 Summary for Policymakers (2021)

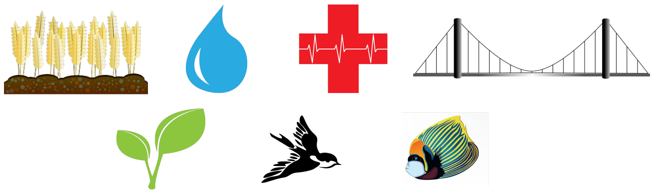
Climate change adaptation

Adaptation: Responding to the effects of a changing climate

1. Measuring and predicting risks
   - **Risk**: Impact x probability

2. Strengthening adaptive capacity
   - **Robustness:** Withstanding a range of outcomes with no/minimal impact
   - **Resilience:** Recovering quickly after impact

Human & ecological systems



Connections with UN SDGs

Figure source (bottom): United Nations

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Takeaways: Introduction to climate change

Rapid action is needed on climate change

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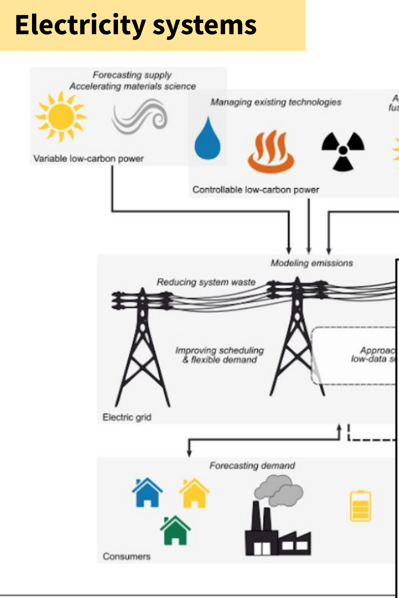
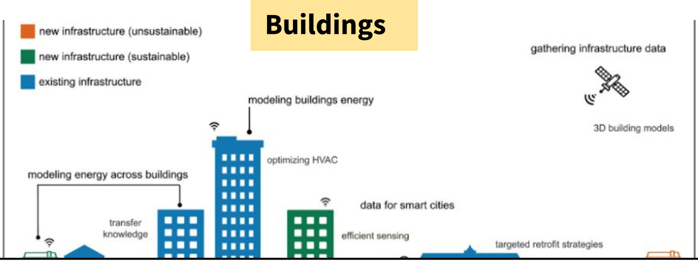
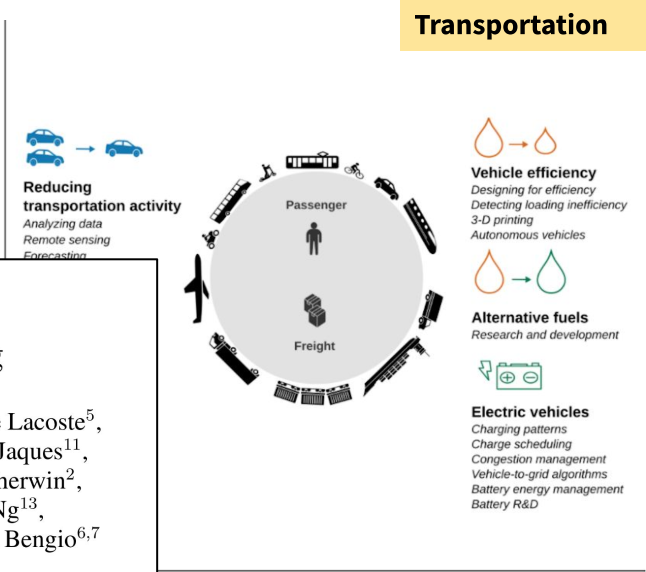
Takeaways and how to get involved

Roles for ML in climate action

Considerations in evaluating applications







Tackling Climate Change with Machine Learning

David Rolnick[1*], Priya L. Donti[2], Lynn H. Kaack[3], Kelly Kochanski[4], Alexandre Lacoste[5], Kris Sankaran[6,7], Andrew Slavin Ross[8], Nikola Milojevic-Dupont[9,10], Natasha Jaques[11], Anna Waldman-Brown[11], Alexandra Luccioni[6,7], Tegan Maharaj[6,7], Evan D. Sherwin[2], S. Karthik Mukkavilli[6,7], Konrad P. Kording[1], Carla Gomes[12], Andrew Y. Ng[13], Demis Hassabis[14], John C. Platt[15], Felix Creutzig[9,10], Jennifer Chayes[16], Yoshua Bengio[6,7]

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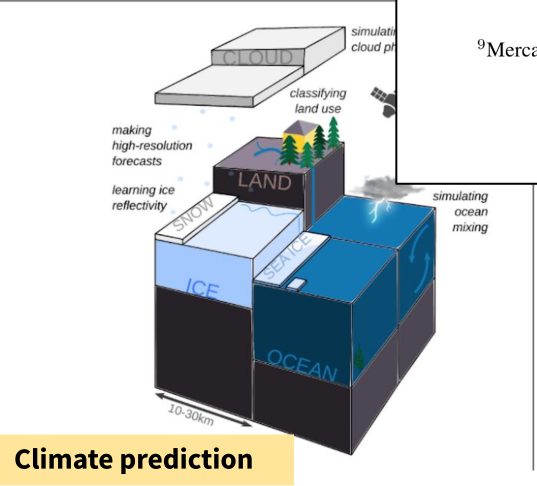
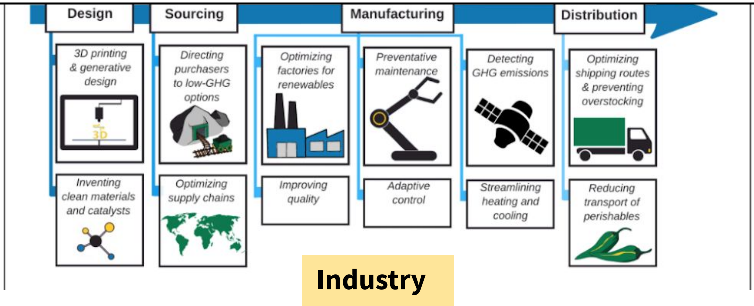
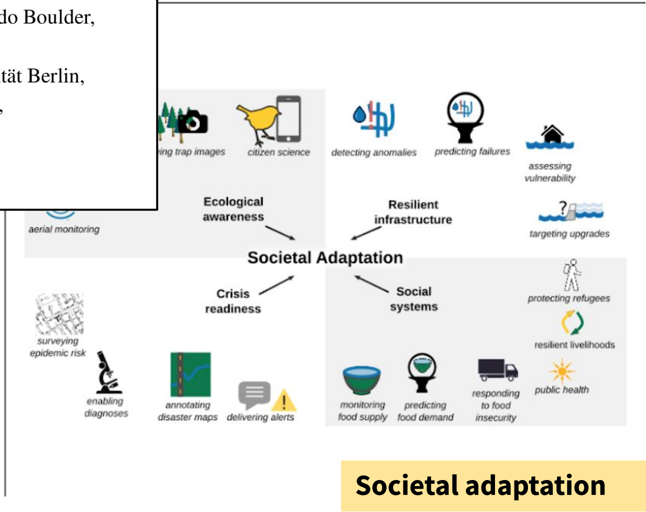
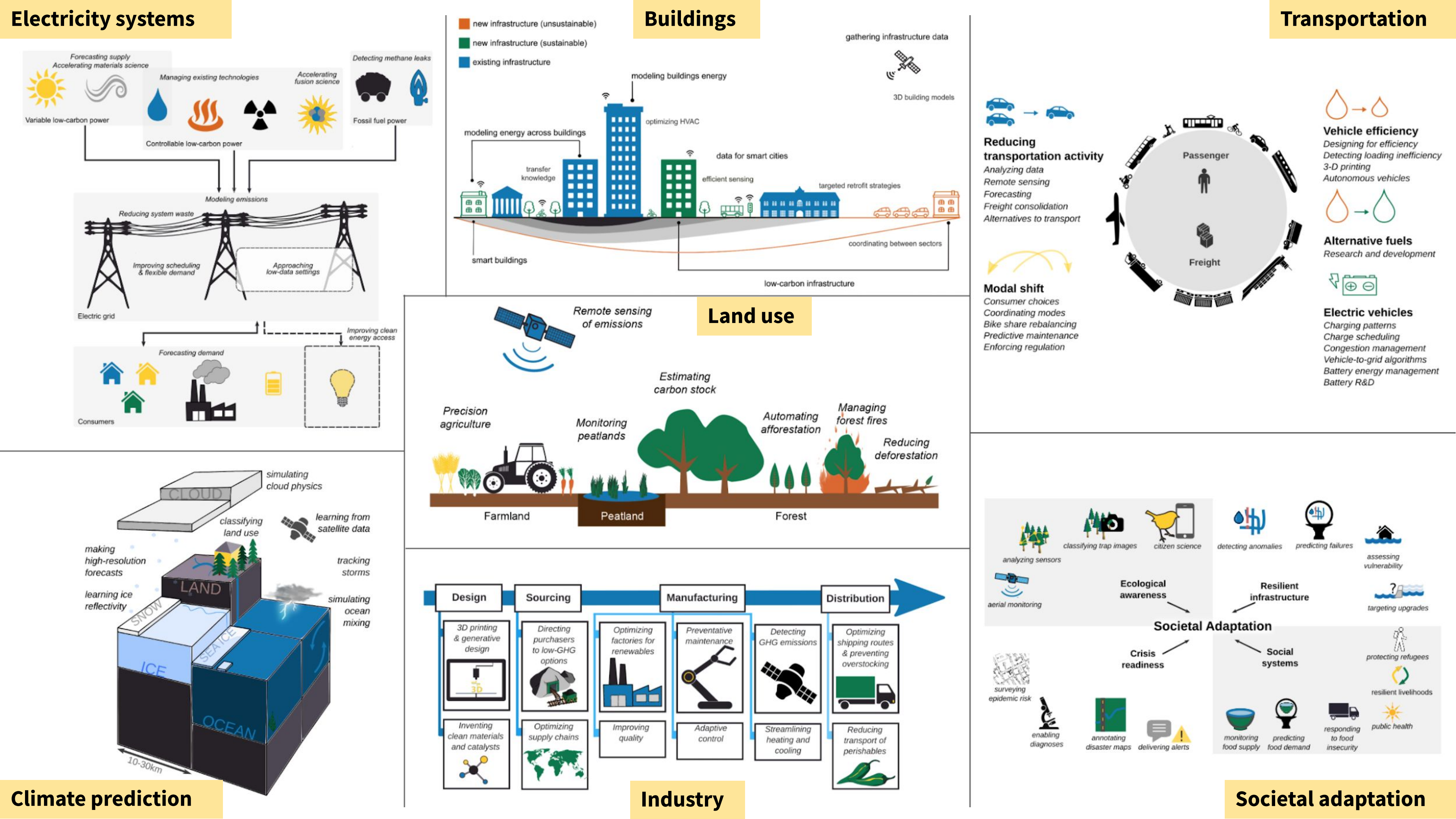


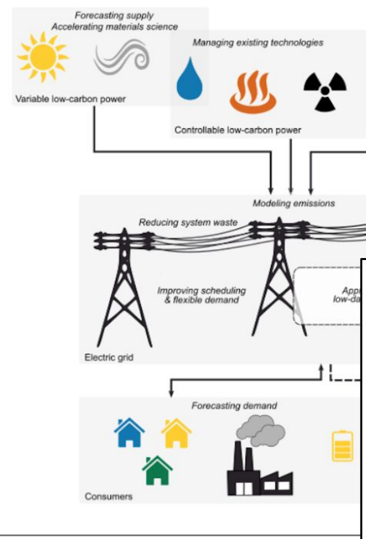




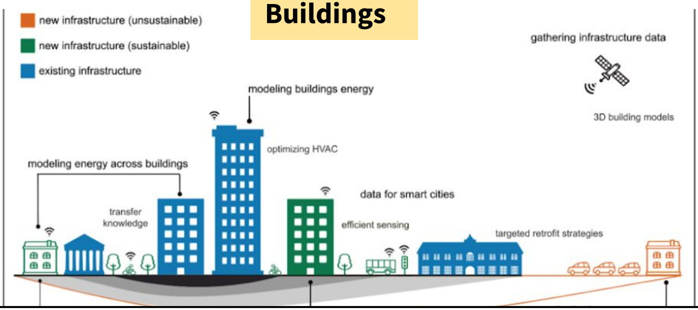


Electricity systems
Forecasting supply
Accelerating materials science
Variable low-carbon power
Managing existing technologies
Accelerating fusion science
Controllable low-carbon power
Detecting methane leaks
Fossil fuel power
Modeling emissions
Reducing system waste
Improving scheduling & flexible demand
Approaching low-data settings
Electric grid
Improving clean energy access
Forecasting demand
Consumers
Buildings
new infrastructure (unsustainable)
new infrastructure (sustainable)
existing infrastructure
gathering infrastructure data
3D building models
modeling buildings energy
optimizing HVAC
modeling energy across buildings
transfer knowledge
data for smart cities
efficient sensing
targeted retrofit strategies
coordinating between sectors
smart buildings
low-carbon infrastructure
Transportation
Reducing transportation activity
Analyzing data
Remote sensing
Forecasting
Freight consolidation
Alternatives to transport
Modal shift
Consumer choices
Coordinating modes
Bike share rebalancing
Predictive maintenance
Enforcing regulation
Passenger
Freight
Vehicle efficiency
Designing for efficiency
Detecting loading inefficiency
3-D printing
Autonomous vehicles
Alternative fuels
Research and development
Electric vehicles
Charging patterns
Charge scheduling
Congestion management
Vehicle-to-grid algorithms
Battery energy management
Battery R&D
Land use
Remote sensing of emissions
Estimating carbon stock
Precision agriculture
Monitoring peatlands
Automating afforestation
Managing forest fires
Reducing deforestation
Farmland
Peatland
Forest
Climate prediction
simulating cloud physics
CLOUD
classifying land use
learning from satellite data
making high-resolution forecasts
tracking storms
learning ice reflectivity
simulating ocean mixing
LAND
SNOW
SEA ICE
ICE
OCEAN
10-30km
Industry
Design
Sourcing
Manufacturing
Distribution
3D printing & generative design
Directing purchasers to low-GHG options
Optimizing factories for renewables
Preventative maintenance
Detecting GHG emissions
Optimizing shipping routes & preventing overstocking
Inventing clean materials and catalysts
Optimizing supply chains
Improving quality
Adaptive control
Streamlining heating and cooling
Reducing transport of perishables
Societal adaptation
analyzing sensors
classifying trap images
citizen science
detecting anomalies
predicting failures
assessing vulnerability
aerial monitoring
Ecological awareness
Resilient infrastructure
targeting upgrades
Societal Adaptation
Crisis readiness
Social systems
surveying epidemic risk
protecting refugees
resilient livelihoods
enabling diagnoses
annotating disaster maps
delivering alerts
monitoring food supply
predicting food demand
responding to food insecurity
public health

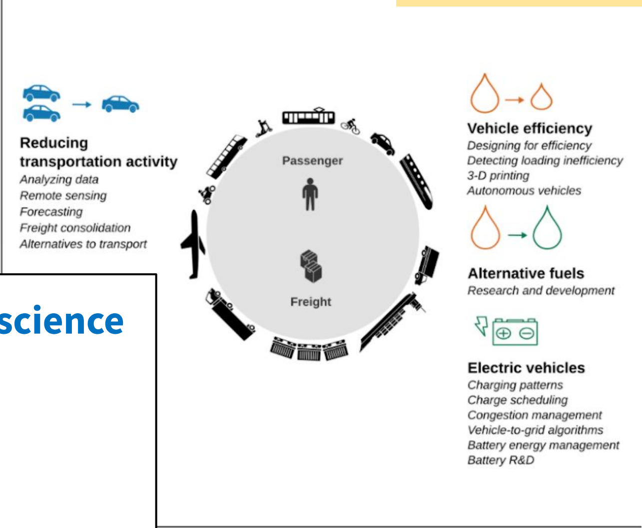
Electricity systems



Buildings



Transportation



Roles for ML in mitigation, adaptation, & climate science

Distilling raw data into actionable information

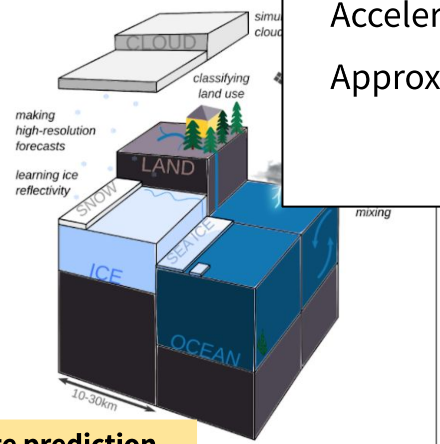
Optimizing complex systems

Improving predictions

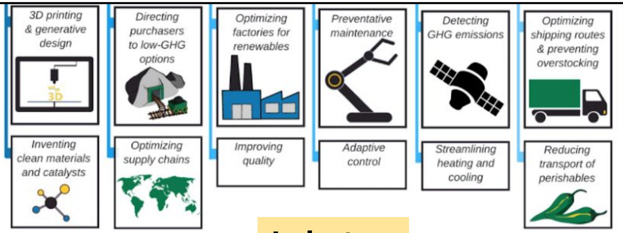
Accelerating scientific discovery

Approximating time-intensive simulations

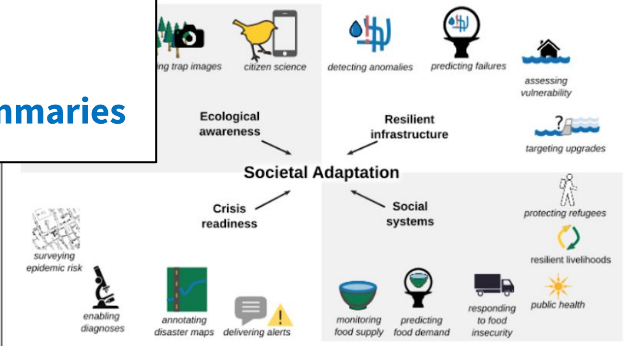
See also: **https://www.climatechange.ai/summaries**



Climate prediction



Industry

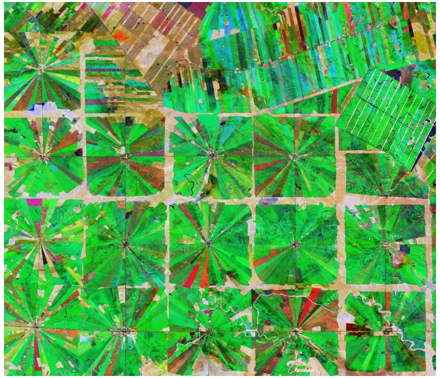


Societal adaptation

1. Distilling raw data

Role: Distilling raw data into actionable information

Some relevant ML areas: Computer vision, natural language processing



Examples

- Mapping deforestation and carbon stock [M]
- Gathering data on building footprints/heights [M]
- Evaluating coastal flood risk [A]
- Parsing corporate disclosures for climate-relevant info [A]

2. Optimizing complex systems

Role: Improving efficient operation of complex, automated systems

Some relevant ML areas: Optimization, control, reinforcement learning

Examples

- Controlling heating/cooling systems efficiently [M]
- Optimizing rail and multimodal transport [M]
- Demand response in electrical grids [M]

Note: Beware of misaligned objectives and rebound effects

3. Improving predictions

Role: Forecasts and time series predictions

Some relevant ML areas: Time series analysis, computer vision, Bayesian methods

Examples

- "Nowcasting" for solar/wind power [M]
- Forecasting electricity demand [M]
- Predicting crop yield from remote sensing data [A]

4. Accelerating scientific discovery

Role: Suggesting experiments in order to speed up the design process

Some relevant ML areas: Generative models, active learning, reinforcement learning, graph neural networks

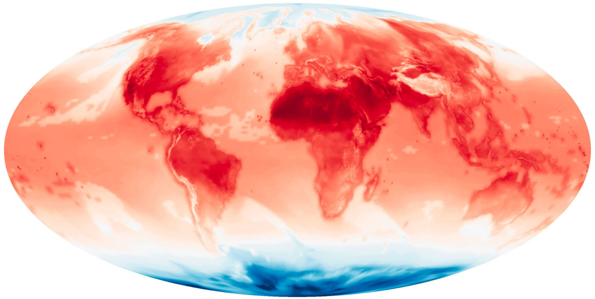
Examples

- Identifying candidate materials for batteries, photovoltaics, and energy-related catalysts [M]
- Algorithms for controlling fusion reactors [M]

5. Approximating simulations

Role: Accelerating time-intensive, often physics-based, simulations

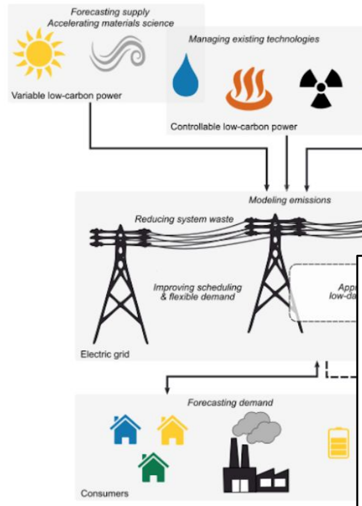
Some relevant ML areas:
Physics-informed ML, computer vision, interpretable ML, causal ML



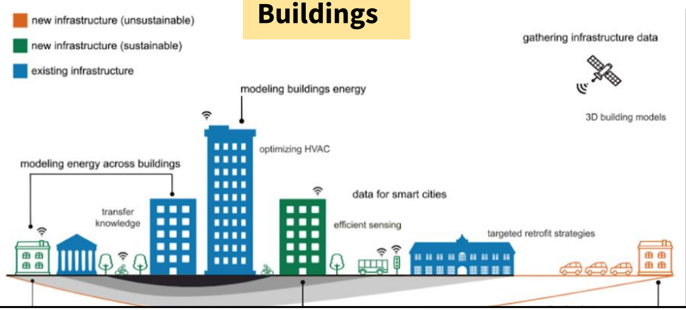
Examples

- Superresolution of predictions from climate models [A]
- Simulating portions of car aerodynamics [M]
- Speeding up planning models for electrical grids [M]

Electricity systems



Buildings



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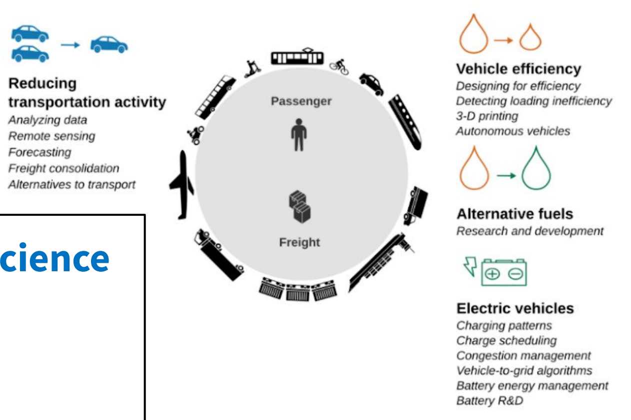

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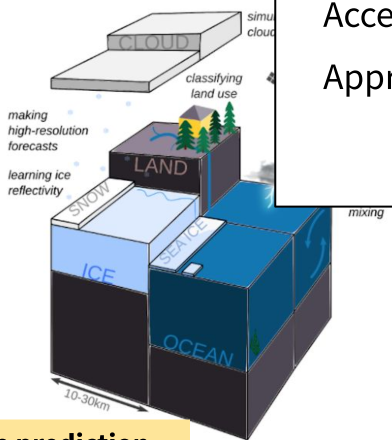
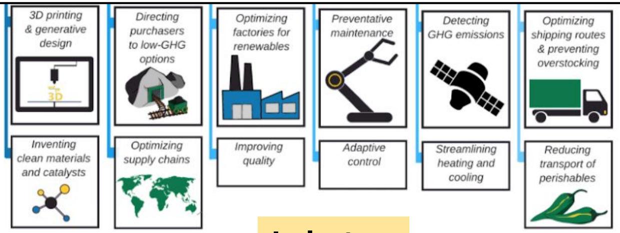


Climate prediction



Industry

Societal adaptation

Questions that we asked in identifying priorities

- **Is ML needed** to address the problem?
- What is the **scope** of the impact? (in rough terms)
- What is the **time horizon** of the impact?
- What is the **likelihood** that a solution can be found?
- Can a solution feasibly be **deployed**?
- What are the potential **side effects** of deploying the candidate solution?
- Who are the **relevant stakeholders** who are involved in or affected by the application?

Key considerations

ML is not a silver bullet and is only relevant sometimes

High-impact applications are not always flashy

Interdisciplinary collaboration

- Scoping the right problems
- Incorporating relevant domain information
- Shaping pathways to impact

Equity considerations

- Empowering diverse stakeholders
- Selecting and prioritizing problems
- Ensuring data is representative

Opportunities for innovation in ML

Sophisticated algorithms may be required, but aren't always

Any innovations should be shaped by needs of the relevant application

- Physics/engineering constraints or robustness guarantees
- Interpretability or causality
- Uncertainty quantification
- Generalization, e.g. across geographies, under non-stationarity, or with limited data

See our [ICML 2022 tutorial]

Lecture outline

Introduction to climate change

Opportunities for ML in climate action

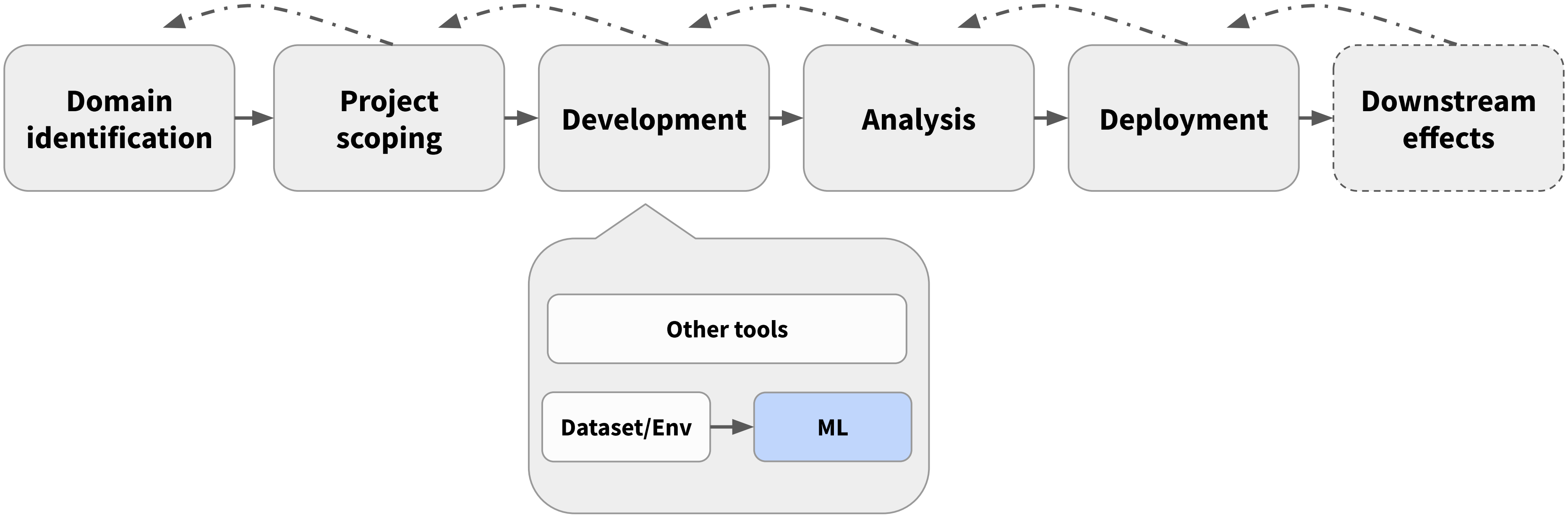
Considerations for research and deployment

- Data & metrics
- Stakeholder engagement
- Responsible AI considerations

Is ML a help or hindrance for climate action?

Takeaways and how to get involved

ML-for-climate: Pathway to impact



Developing data, simulators, and metrics

Data: Collection, annotation, collation, inference, and/or licensing

- Note: "Data" can mean different things to different communities

Simulators: Needed for innovations in physical domains

- E.g., power systems, transport, buildings, heavy industry

Evaluation metrics: Need agreement and iteration from ML researchers, domain researchers, deployers, and other affected stakeholders

Resources and venues

- CCAI dataset wishlist (www.climatechange.ai/dataset-wishlist.pdf)
- Lacuna Fund funding for climate datasets
- NeurIPS Datasets and Benchmarks track

Responsible AI for climate action

Mitigating biases in data and models

- E.g., Buildings data: Housing discrimination, geographic disparities in availability
- E.g., Weather models: Calibration may be optimized for particular regions

Improving trustworthiness and accountability

- Safety and robustness: Critical in, e.g., power systems and industrial operations
- Interpretability and auditability: Critical in, e.g., policymaking contexts

Centering equity and climate justice

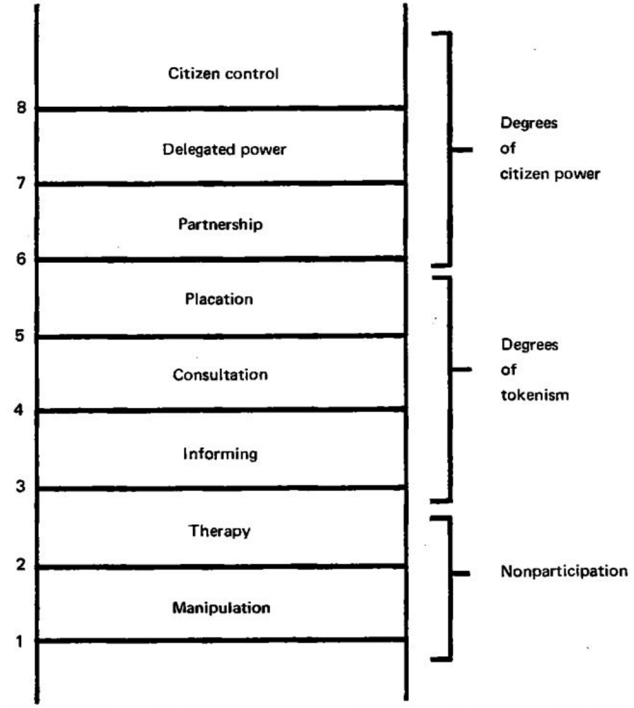
- Centering diverse stakeholders: E.g., industrial ag vs. smallholder farmers
- Avoiding centralization: Democratized capacity and compute, digital divide
- Avoiding digital colonialism: E.g., smart meters, analysis of remote sensing data

Importance of stakeholder engagement

Stakeholder types (e.g.)

- Researchers (tech & social sciences)
- Implementing entities and industries
- End users
- Policymakers
- Other affected parties

Meaningful engagement required



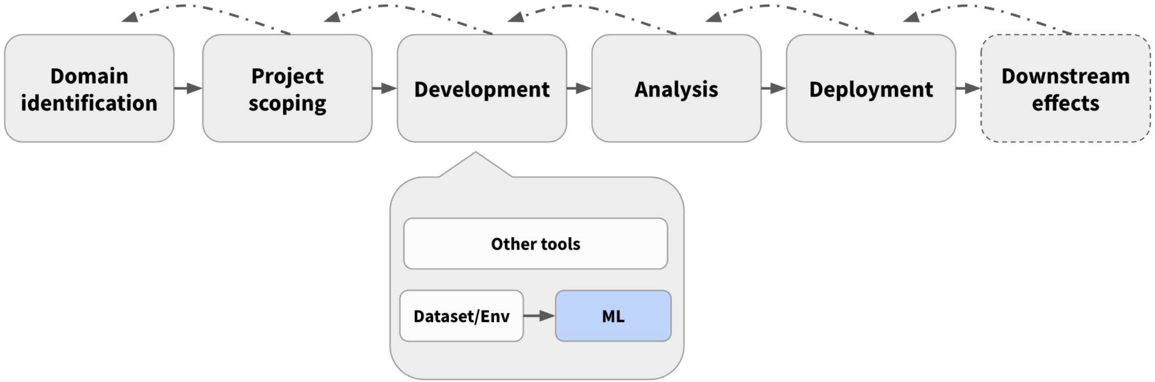
Arnstein's Ladder of Citizen Participation

Figure source: Arnstein, S. R. (1969). A ladder of citizen participation. *Journal of the American Institute of Planners*, *35*(4), 216-224.

Takeaways: Considerations for research & deployment

Consider the full pathway to impact, including

- Data, simulators, metrics
- Responsible AI & climate considerations
- Stakeholder engagement



Lecture outline

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Takeaways and how to get involved

What is ML's carbon footprint?

What can one do to shape the overall impact?

ML’s carbon footprint

ML applications in climate change mitigation

Emissions from ML computation & hardware

ML’s system-level impacts

ML applications that increase emissions

Kaack, L. H., Donti, P. L., Strubell, E., Kamiya, G., Creutzig, F., & Rolnick, D. (2022). Aligning artificial intelligence with climate change mitigation. *Nature Climate Change*, 1-10.

ML’s carbon footprint

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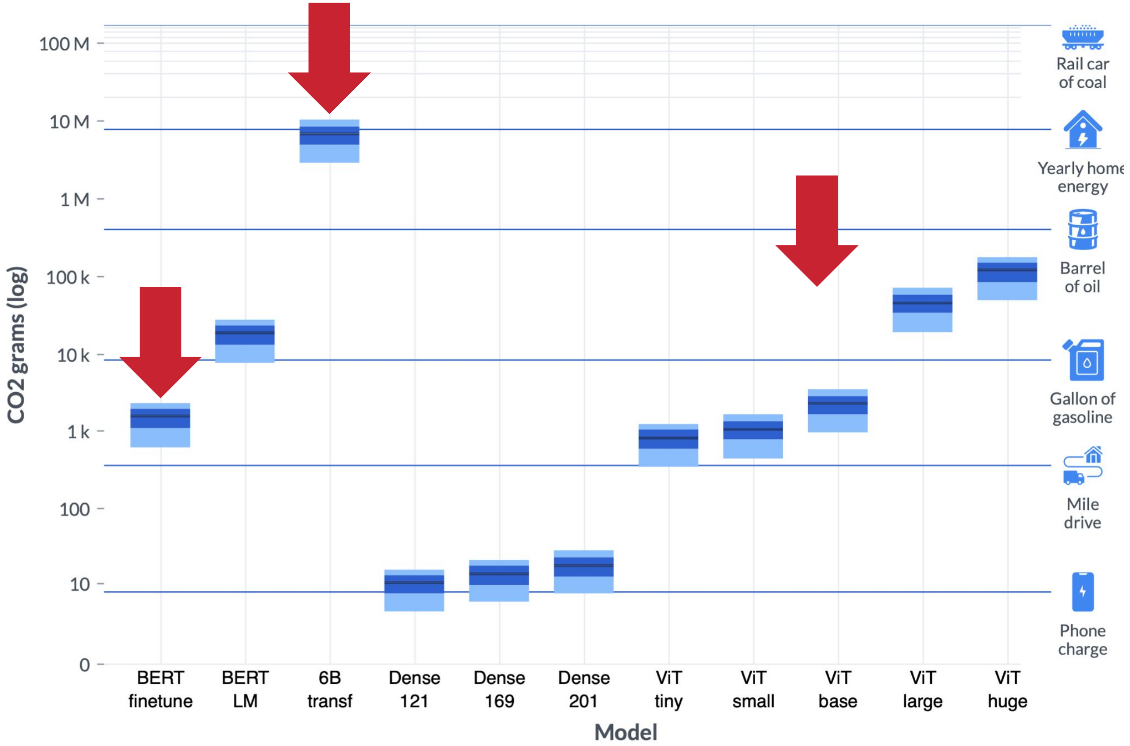
ML’s system-level impacts

Kaack, L. H., Donti, P. L., Strubell, E., Kamiya, G., Creutzig, F., & Rolnick, D. (2022). Aligning artificial intelligence with climate change mitigation. *Nature Climate Change*, 1-10.

Emissions from ML computation



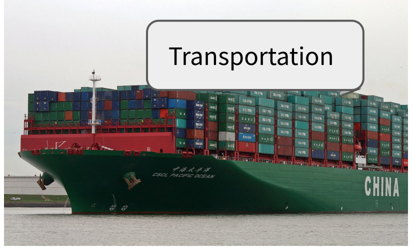
CO2 Relative Size Comparison

Dodge, J., Prewitt, T., Tachet des Combes, R., Odmark, E., Schwartz, R., Strubell, E., ... & Buchanan, W. (2022, June). Measuring the Carbon Intensity of AI in Cloud Instances. In *2022 ACM Conference on Fairness, Accountability, and Transparency* (pp. 1877-1894).

Impacts from ML computation & hardware

Operational emissions from energy consumed during computation

Embodied emissions from production and end-of-life of hardware



ML's carbon footprint

ML applications in climate change mitigation

Emissions from ML computation & hardware

ML's system-level impacts

ML applications that increase emissions

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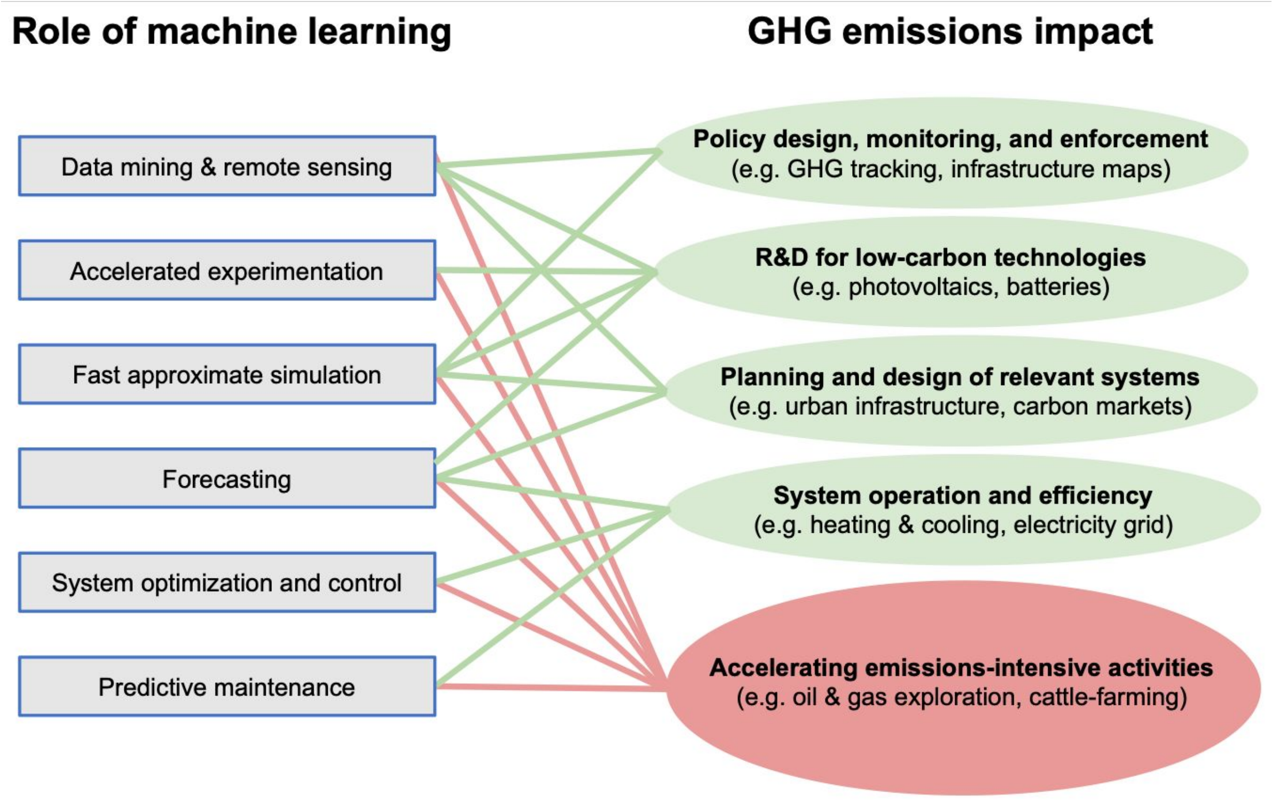
Immediate application impacts

See section on "Opportunities for ML in climate action"



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Broader scope of application impacts

Example: Efficiency improvements in crude oil refining

- Crude oil is turned into lighter hydrocarbons by heat from coker units
- Accurately predicting coke buildup in pipes with ML can help **maintain equipment and reduce energy consumption**
- This application of ML is reducing emissions in the refinery
- The application is also **reducing costs**
- We need to consider how the application affects emissions from the energy and economic system as a whole

ML's carbon footprint

Emissions from ML computation & hardware

ML applications in climate change mitigation

ML applications that increase emissions

ML's system-level impacts

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ML's carbon footprint

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Climate change impacts of your ML work

Computing-related:

- **Measure** your footprint with tools such as ML CO2 Impact, CodeCarbon, Carbontracker, or tools specifically for Azure or Hugging Face
- **Reduce** your impacts by choosing more efficient models, and reducing wasteful model retraining and execution

Application-related:

- **Quantify and evaluate** the application impacts where possible
- Be **transparent** about impacts in publications and with stakeholders (quantitatively and qualitatively)
- Choose **what** you (or the ML community) works on

Lecture outline

Introduction to climate change

Opportunities for ML in climate action

Considerations for research and deployment

Is ML a help or hindrance for climate action?

Takeaways and how to get involved

Ways to be involved in ML + climate change

Many job opportunities exist in this space, including in traditional academic research, focused institutes, startups, tech companies, tech teams in non-tech companies, and public bodies for funding, data, procurement, & policy

ML-focused folks can **include climate-relevant applications** in the set of problems that motivate their work & **build collaborations with domain experts**

Climate-focused folks can **learn about relevant ML methods** and where they may be applicable & can **build collaborations with ML experts**

From ML and tech, working explicitly on climate problems isn't the only way to help - consider how to better **align your existing projects** with climate goals

Consider becoming a bridge btw. specific fields or sectors (e.g. ML + agriculture)

Other relevant resources

<u>Selected communities & events</u>

- **Energy:** ACM e-Energy, IEEE Power & Energy, PSCC, BuildSys, AI.EPRI
- **Land use:** GRSS-IEEE, Int'l Soc. of Precision Ag, Restor, Global Forest Watch
- **Climate & Earth science:** Climate Informatics, AGU/EGU, Phi-Week
- **Biodiversity:** AI for Conservation slack, WILDLABS, GEO BON
- **General:** CompSustNet (community & doctoral consortium)

<u>Publication venues:</u> ICML/NeurIPS/CVPR/etc, special track of JMLR on climate, Environmental Data Science, ACM COMPASS, many domain-specific and general interest venues

<u>More info</u> in the **Climate Change AI monthly newsletter**

Datasets and challenges

Energy: CityLearn, OPFLearn, ARPA-E GO, PowerGridworld, L2RPN, BeoBench, Building Data Genome, bbd.labworks.org, COBS, BOPTEST/ACTB, Open Catalyst

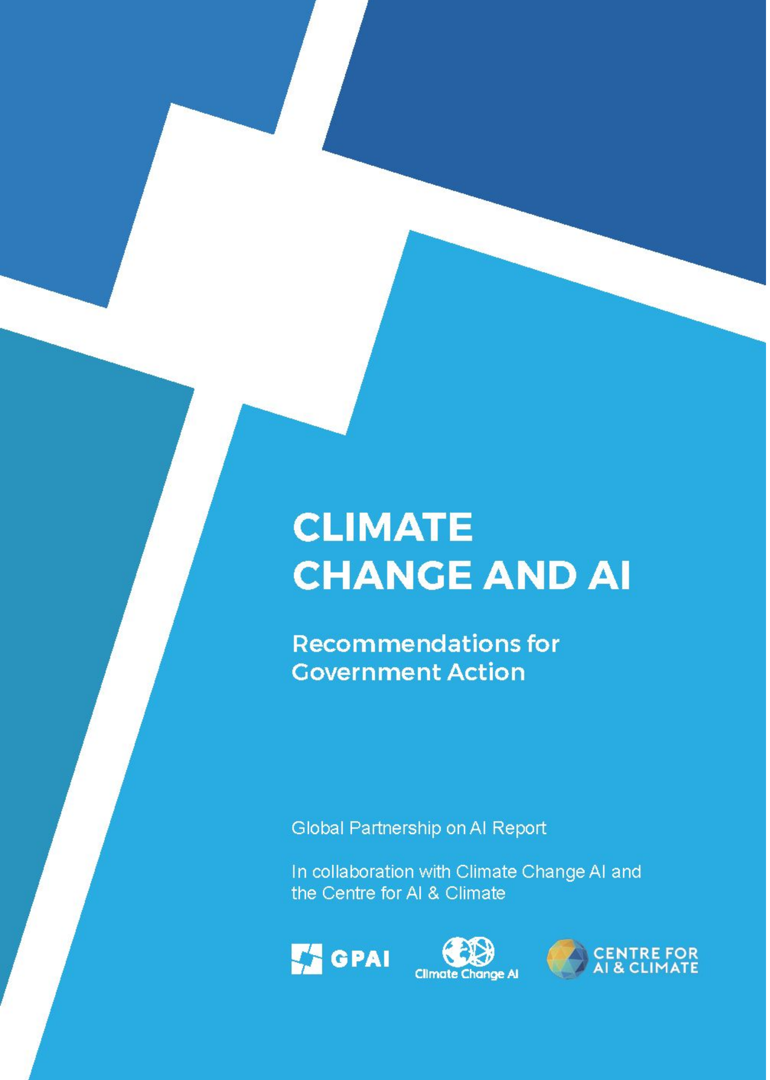
Land use: TorchGeo, blutjens/awesome-forests, CropHarvest, Radiant ML Hub, LandCoverNet, Agriculture-Vision, chrieke/awesome-satellite-imagery-datasets

Climate & Earth science: mldata.pangeo.io, ClimateBench, ClimART, CauseMe

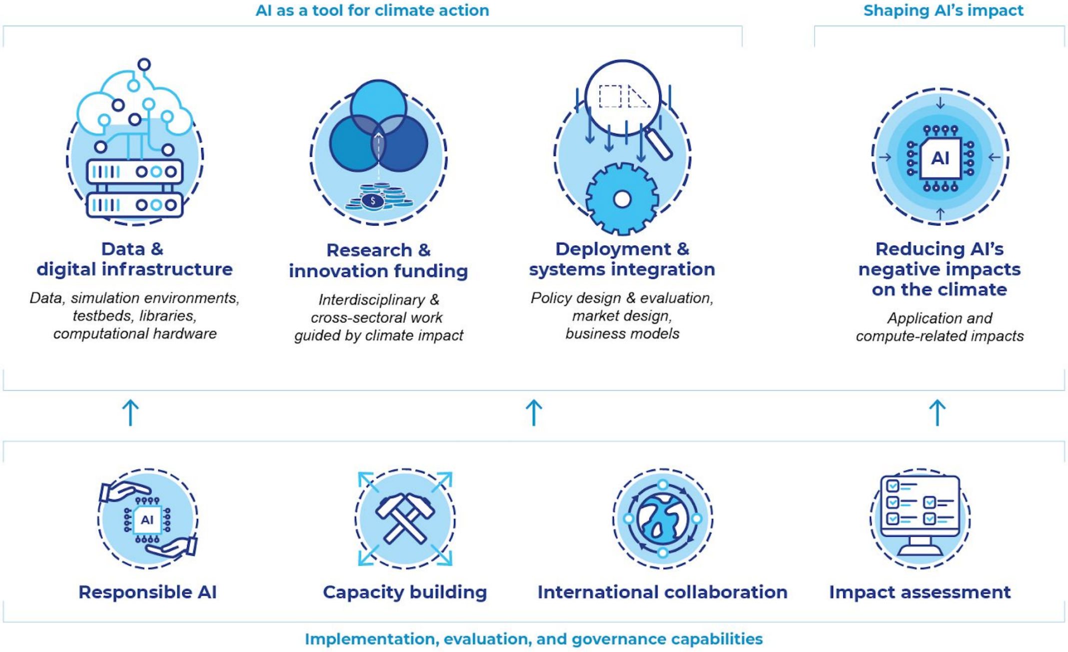
Adaptation: wandb/droughtwatch, Global Flood Database, FloodNet, ITU GEOAI

Biodiversity: iNat dataset, LifeCLEF, FGVC, iWildCam, Movebank

More info (or contribute) at **wiki.climatechange.ai** and practice with **climatechange.ai/tutorials**

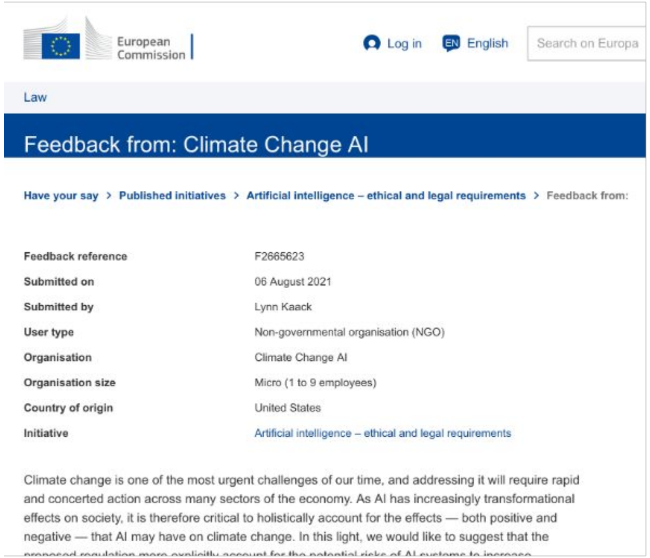

CLIMATE CHANGE AND AI
Recommendations for Government Action
Global Partnership on AI Report
In collaboration with Climate Change AI and the Centre for AI & Climate
GPAI
Climate Change AI
CENTRE FOR AI & CLIMATE

Policy


AI as a tool for climate action
Shaping AI's impact
Data & digital infrastructure
Data, simulation environments, testbeds, libraries, computational hardware
Research & innovation funding
Interdisciplinary & cross-sectoral work guided by climate impact
Deployment & systems integration
Policy design & evaluation, market design, business models
Reducing AI's negative impacts on the climate
Application and compute-related impacts
AI
Responsible AI
Capacity building
International collaboration
Impact assessment
Implementation, evaluation, and governance capabilities

Opportunities for input

- The US Office of Science and Technology Policy (OSTP) **currently requests information** on national priorities for AI
- Such input is open to anyone in the public
- See for example **CCAI feedback** to the European Union’s AI Act
- The **AI Act** (currently under discussion) may include aspect of the environment and climate change according to newest amendments in the EU Parliament



Climate Change AI

Catalyzing impactful work at the intersection of climate change and AI

Digital resources

Foundational report on climate change and AI (plus summaries and tutorials)

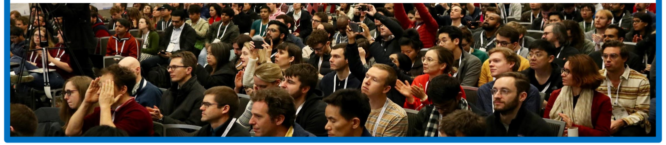
Resource Wiki w/ datasets and additional resources

Conferences & events

Workshop series

- Submit and/or attend
- Mentorship programs

Summer school (multiple tracks)



Funding programs

Global research funding for impactful projects

Community, newsletter, & blog

- Calls for Submissions
- Funding
- Projects & Courses
- Readings
- Jobs

Webinars & happy hours

Learn more & join in:

www.climatechange.ai

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