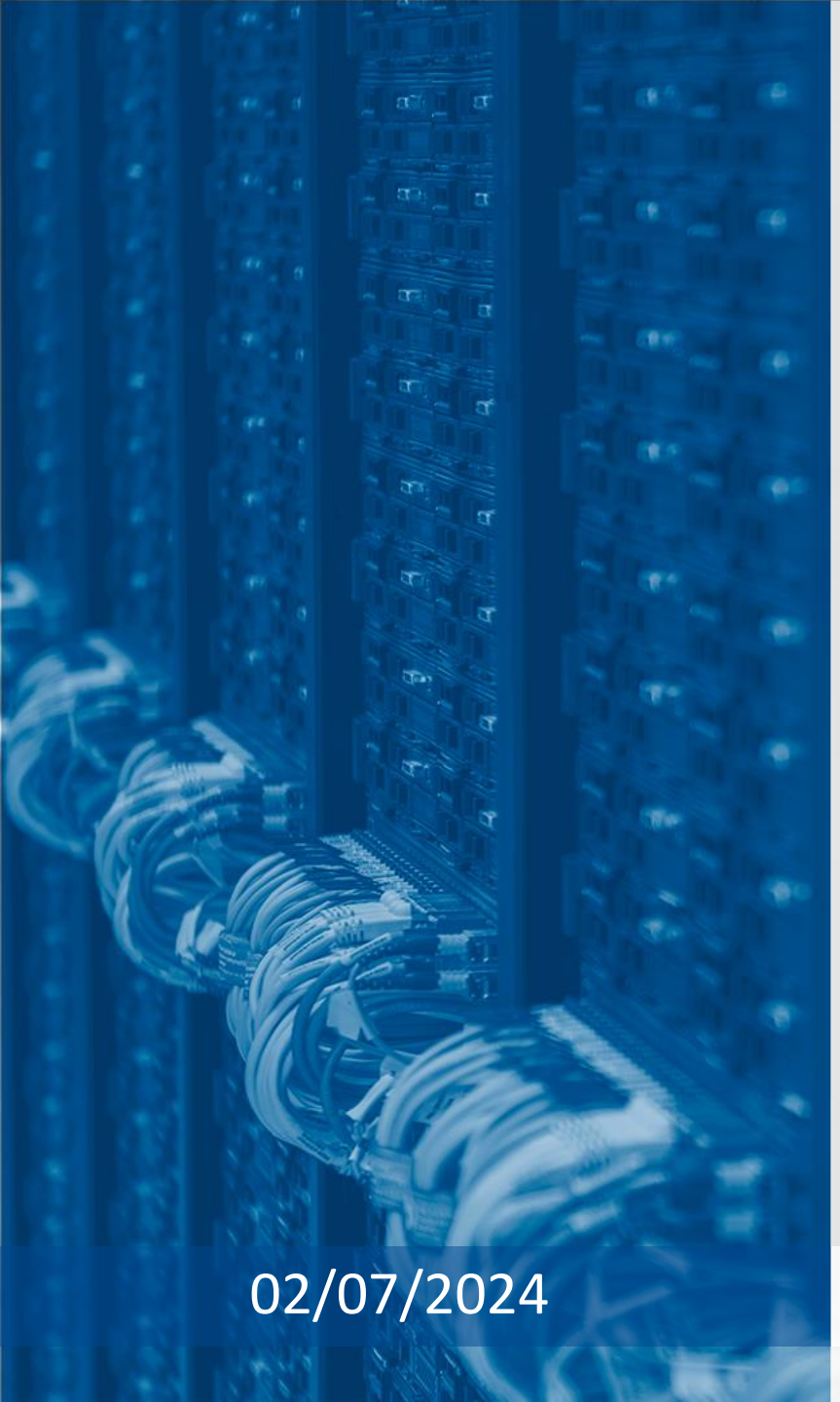

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Blending empirical and dynamical information in forecasting

Stefano Materia

Barcelona Supercomputing Center

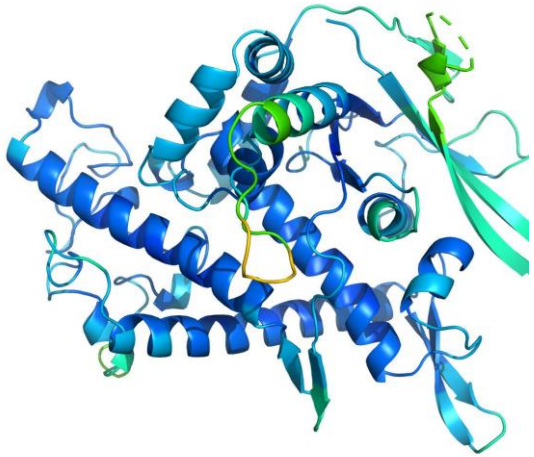
02/07/2024

Workshop on Objective Seasonal Forecast

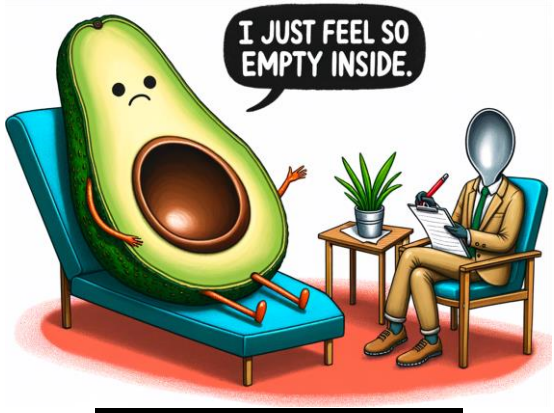
Challenges of current climate predictions

- Increased **anthropogenic climate forcing** -> studies based on older attribution periods may underestimate the effect of global warming on the probability of the unprecedented recent extreme events;
- Many events of the past may be overlooked due to **scarcity of the observation availability**: therefore, ensembles of dynamical models are often entrusted with the detection and attribution of their drivers, with possible misinterpretations;
- **Poor representation of key processes and feedback mechanisms** between different climate components in state-of-the-art numerical climate models, **combined with the uncertainties in the initial state**, make a complex and chaotic system such as the atmosphere extremely challenging to predict.

The AI boom



GitHub Copilot



DALL·E 2

GPT-4

Input

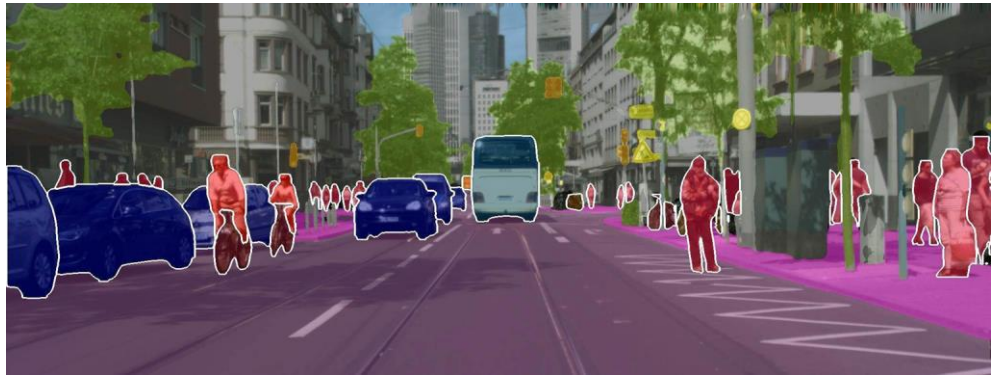
Andrew is free from 11 am to 3 pm, Joanne is free from noon to 2 pm and then 3:30 pm to 5 pm. Hannah is available at noon for half an hour, and then 4 pm to 6 pm. What are some options for start times for a 30 minute meeting for Andrew, Hannah, and Joanne?

Output

Andrew: 11 am - 3 pm
Joanne: 12 pm - 2 pm, 3:30 pm - 5 pm
Hannah: 12 pm - 12:30 pm, 4 pm - 6 pm

Common availability for a 30-minute meeting: 12 pm - 12:30 pm

ChatGPT



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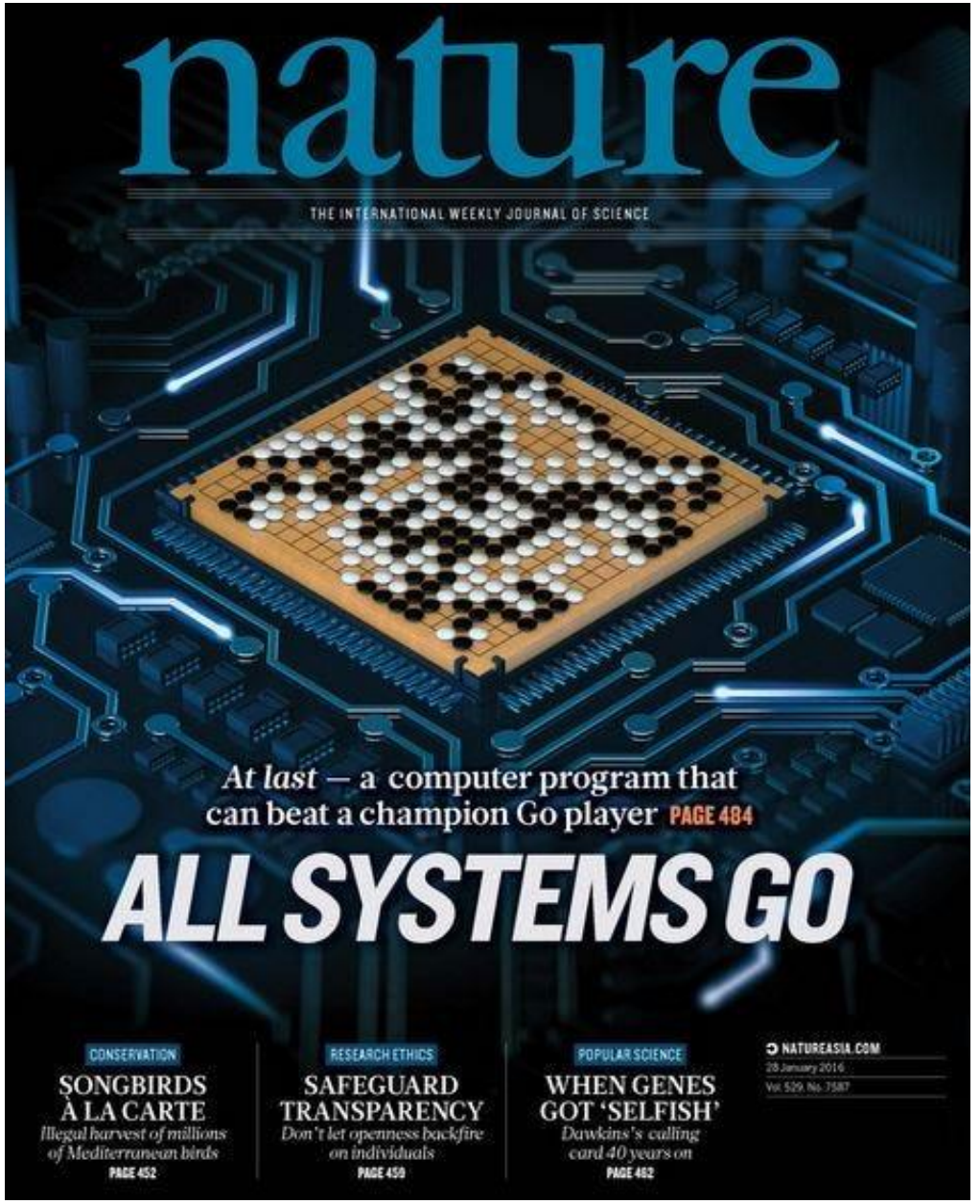
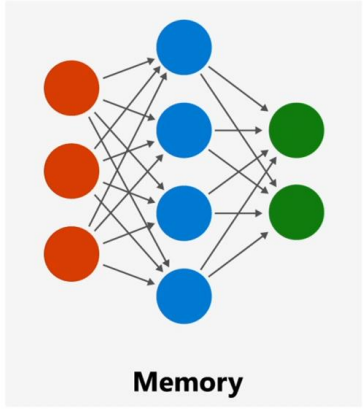
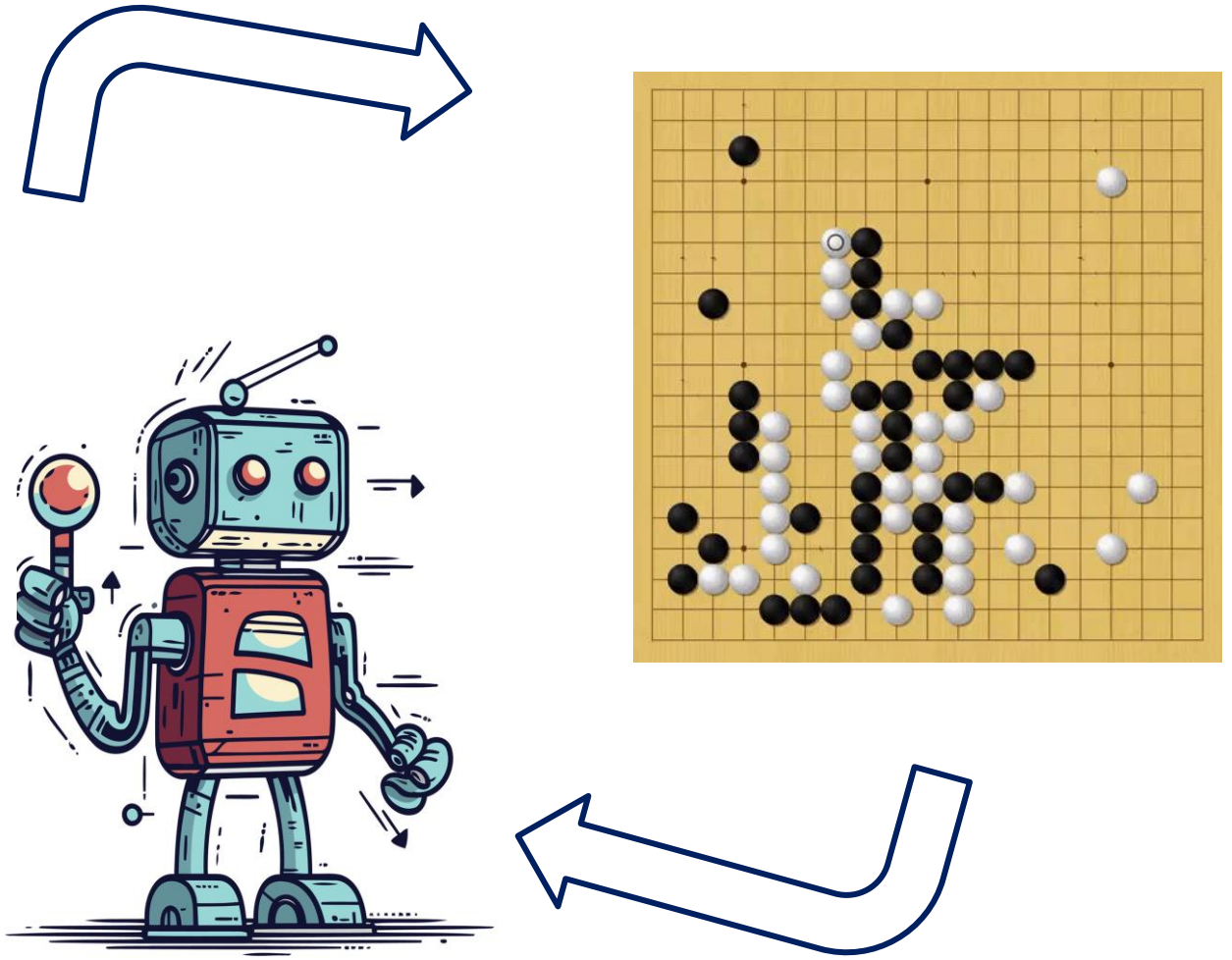
The artificial intelligence beats the world champion of Go



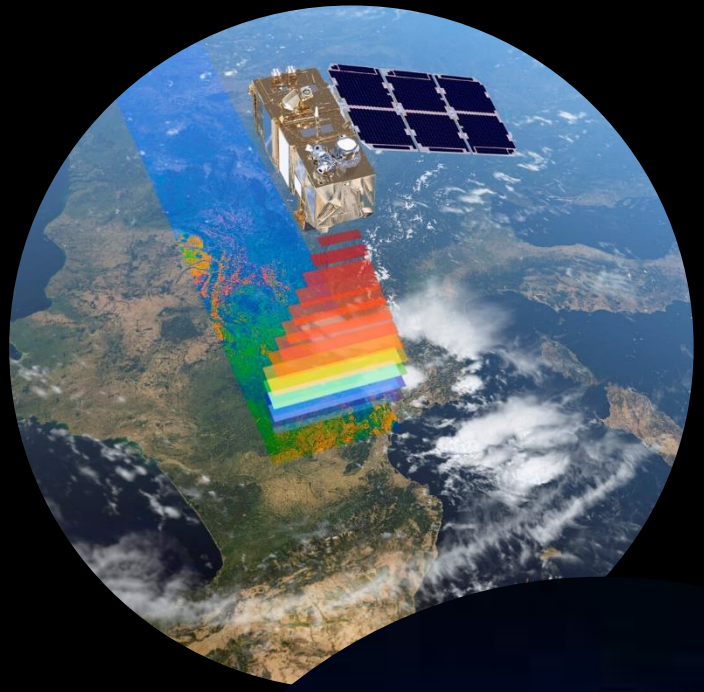
fuente Microsoft





AlphaGo doesn’t know the rules of the game, but can learn and improve from the games played by other players and from his own errors.

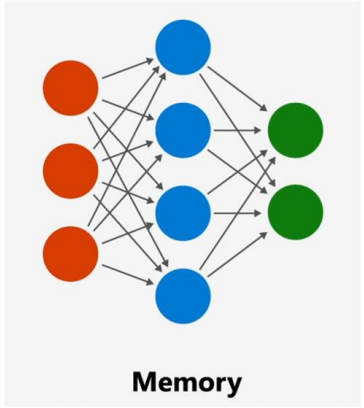
The incredible availability of new earth observation data

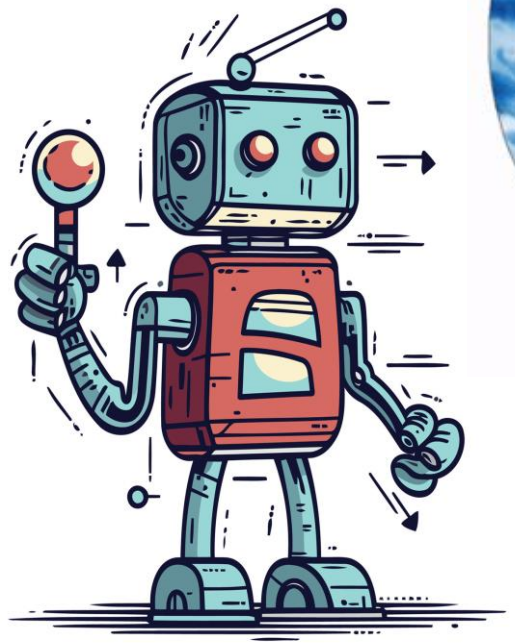


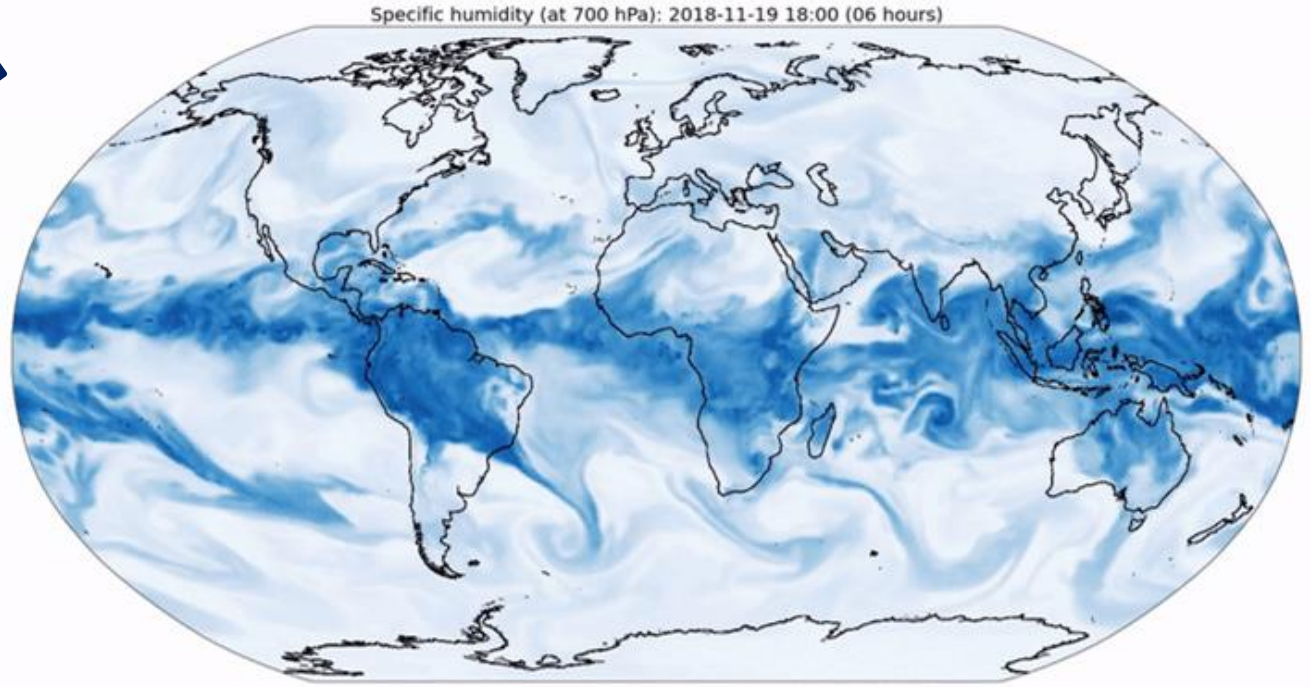
We can use AI also for weather and climate predictions

- Improve the predictions
- Accelerate the calculation
- Save energy and computer resources

fuente Microsoft







Ram et al., 2023

Similarly to AlphaGO, the AI algorithms do not know the physical equations that govern weather and climate, but can generate predictions by learning from earth observations.

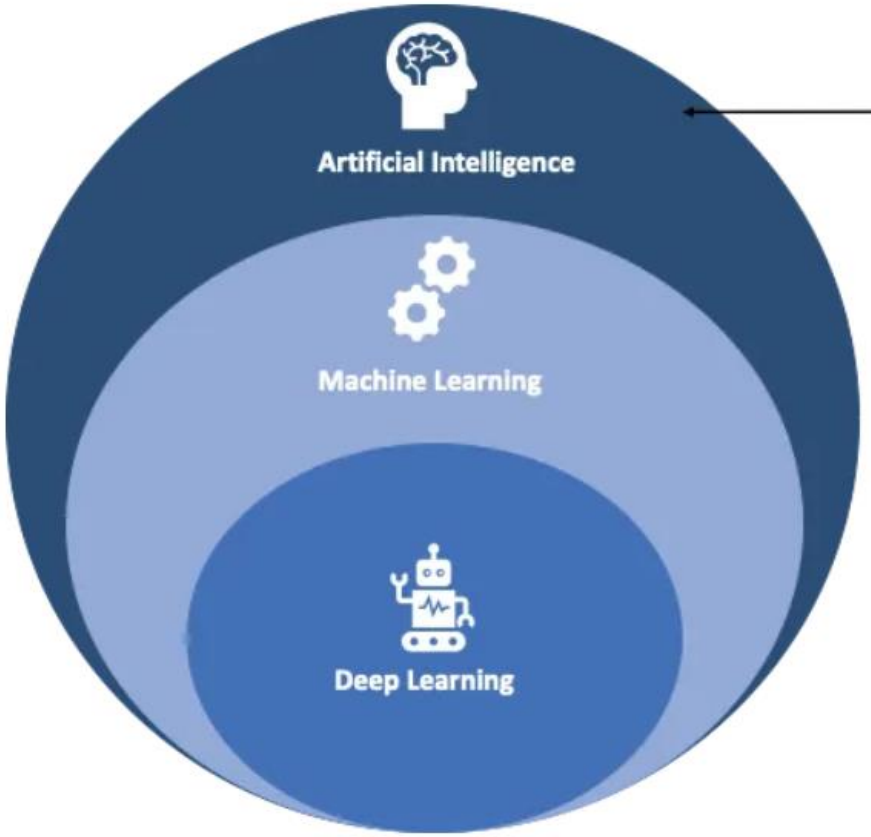
What is AI

Artificial Intelligence (AI) refers to the **ability of machines (computers) to perform tasks** that typically require human intelligence.

These tasks include **learning from experience, understanding language, recognizing patterns, solving problems, and making decisions**.

Essentially, AI enables machines to mimic human cognitive functions.

Artificial intelligence, machine and deep learning

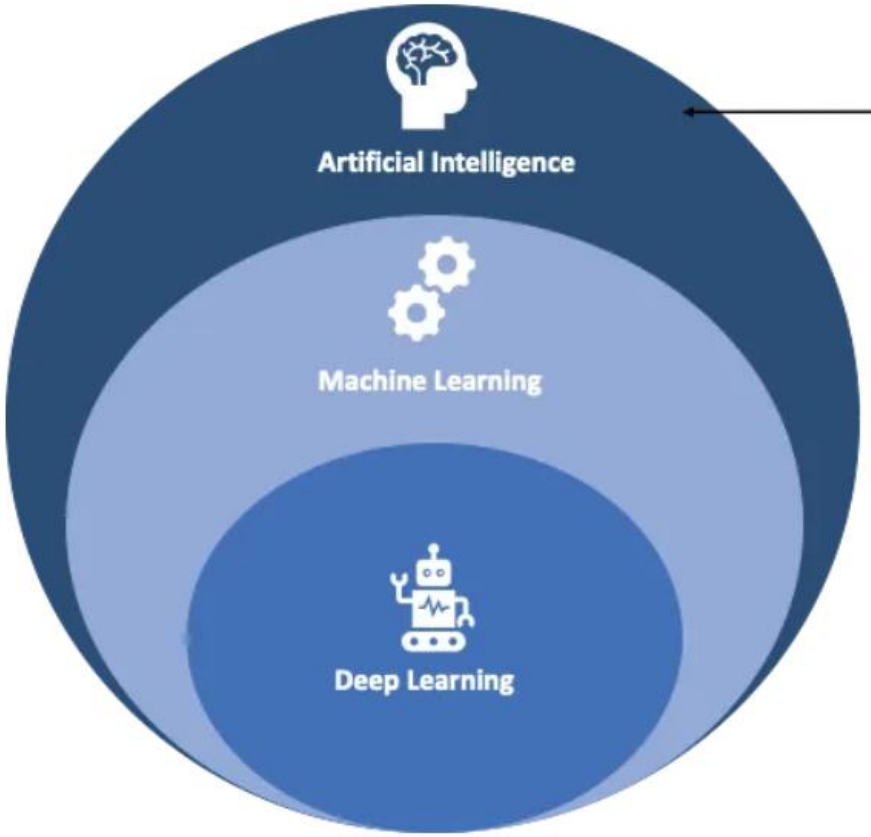


Artificial Intelligence
Technology in which computers behave like humans and have learning capabilities

Machine Learning
Technology in which computers improves its algorithms through learning experience

- Models used to find patterns in data
- Improves accuracy through experience
- Commonly used for tasks such as classification, regression, clustering

Artificial intelligence, machine and deep learning



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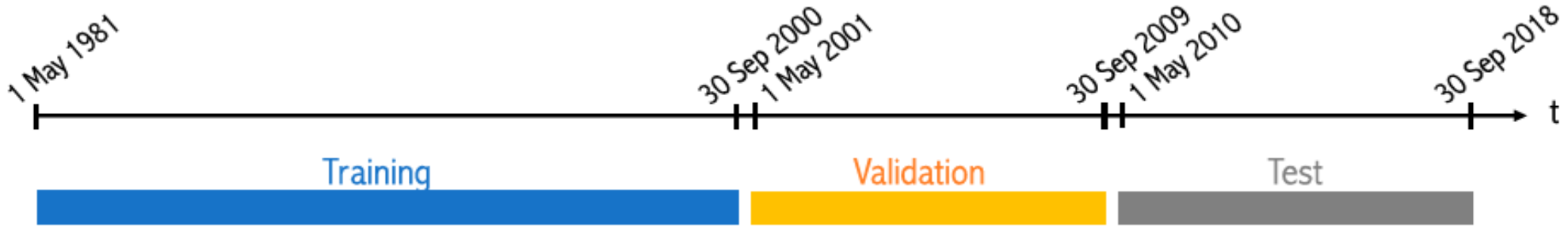
Deep Learning
Type of machine learning algorithms using complex neural networks

- Processes large volumes of unstructured data (images, text)
- Learns hierarchical representations of data
- Requires large datasets for training

How the model is developed

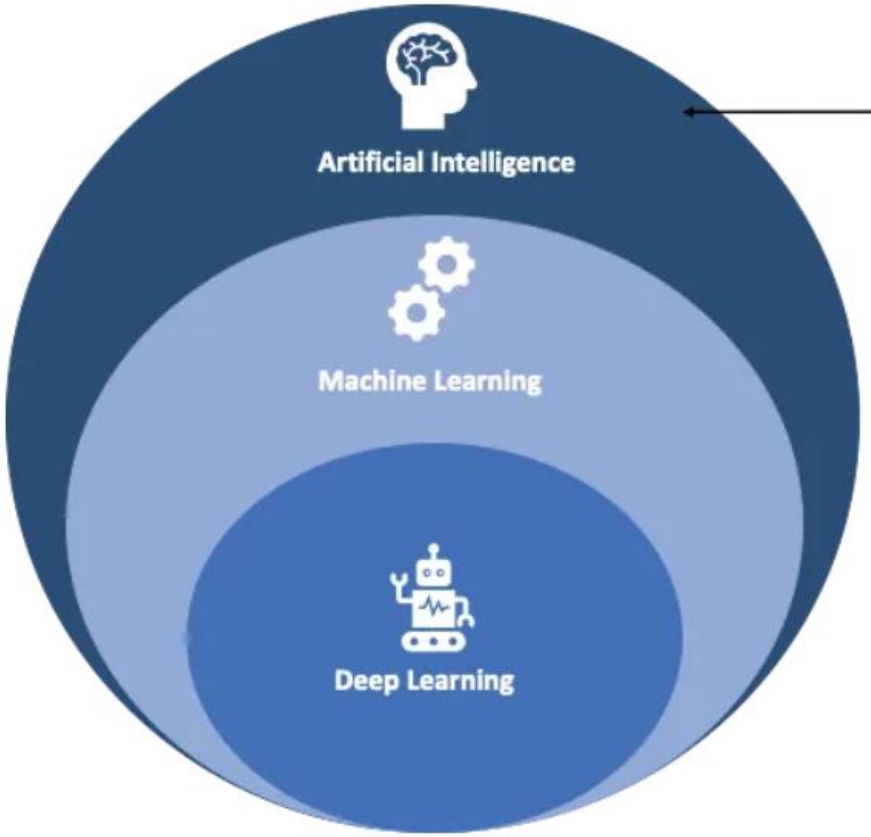


Machine and deep learning are trained on **historical observational data** or **climate model simulations** to recognize patterns and make predictions.

To **tune model** parameters and **prevent overfitting**, the validation dataset is separated to get an optimized model

The final model's performance is assessed on unseen data

Artificial intelligence, machine and deep learning



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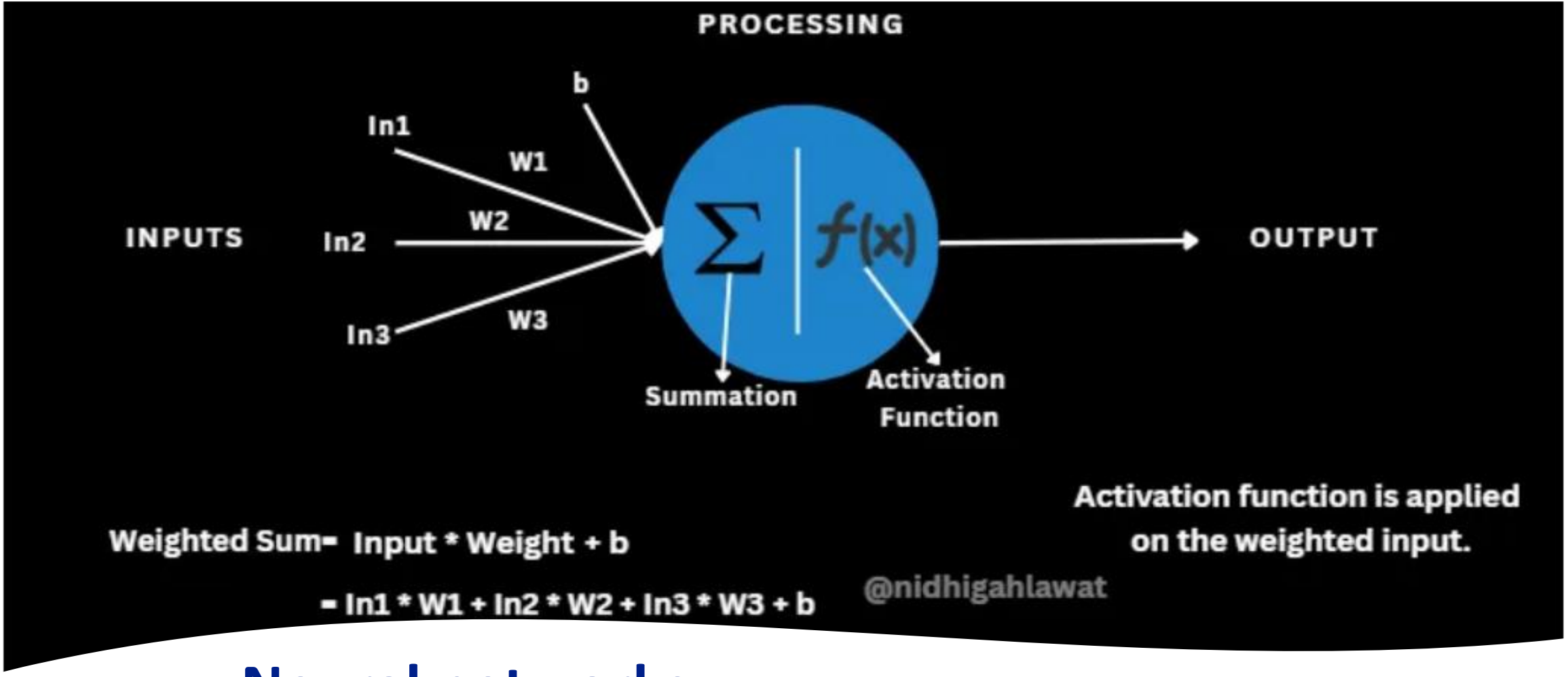


Neural networks

A set of algorithms, modeled after the human brain, **designed to recognize patterns**.

Interpret and analyze training data through “machine perception”

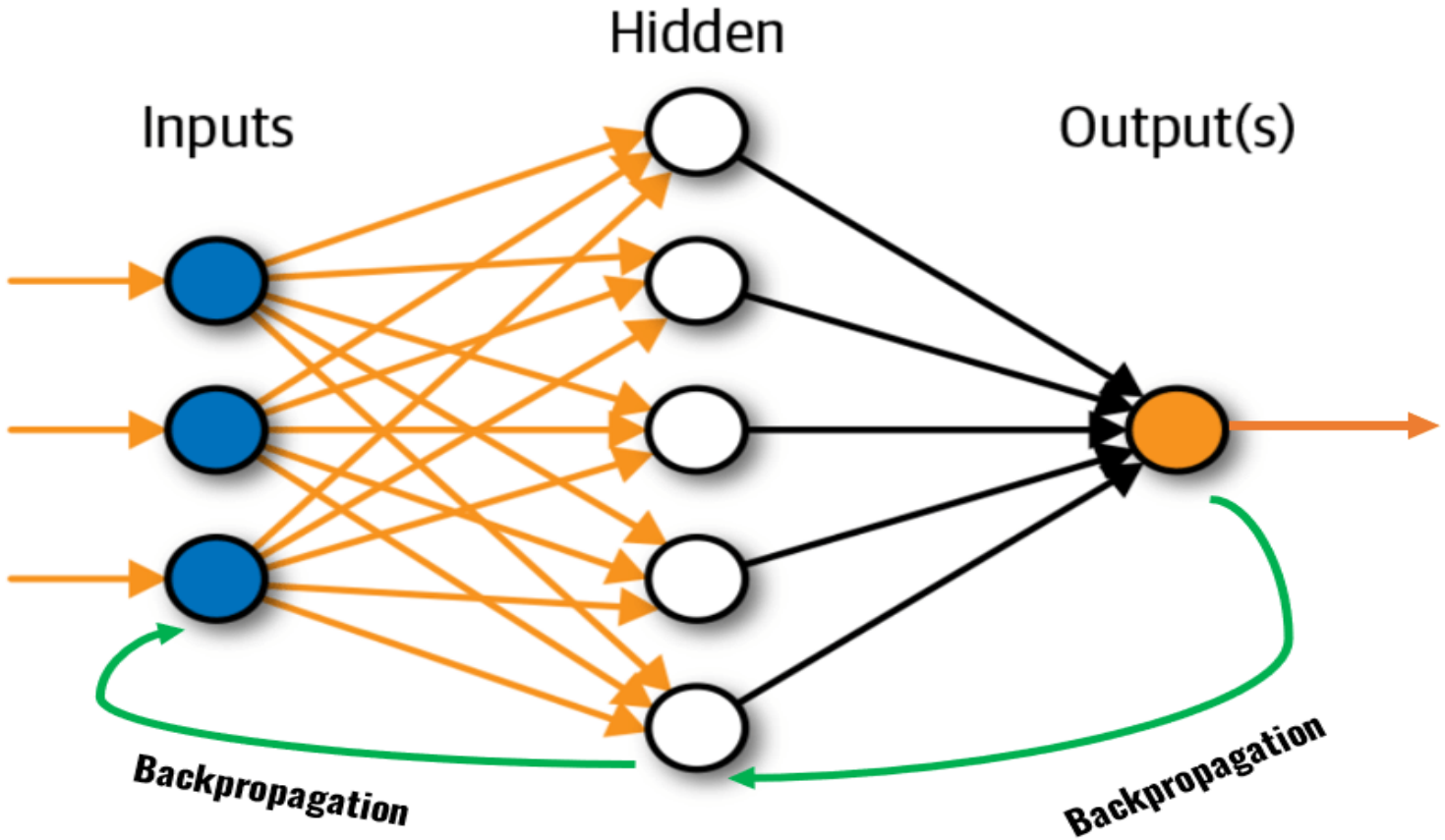
Make predictions **by mimicking interconnected neurons**, just like how our brain processes information.

Layers in neural networks

Input Layer: The input layer is where the neural network receives information or data. It could be pixel values from an image or a **numerical feature, like SST anomaly** in a specific region of the global ocean

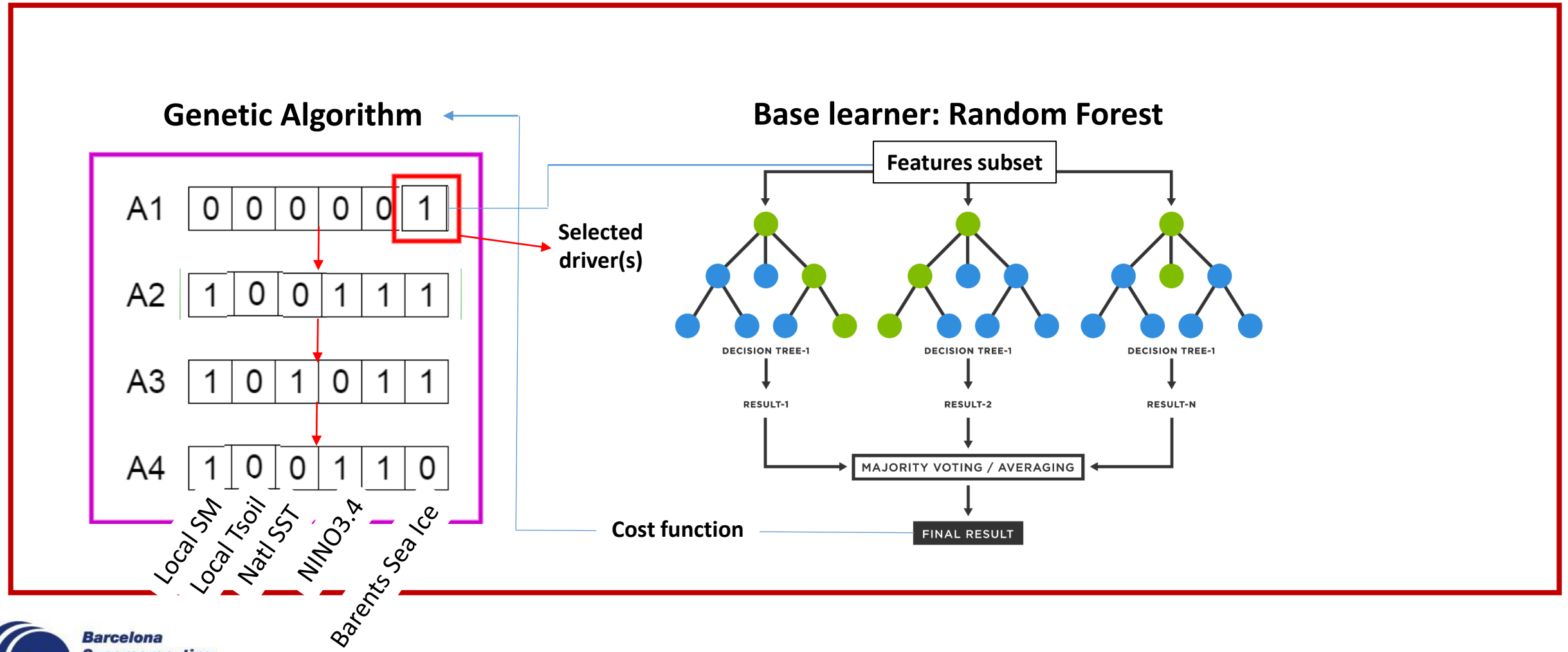
Hidden Layers: The hidden layers consist of interconnected neurons that **perform calculations** (weigh, summing) on the input data. They are responsible for **learning** and extracting meaningful patterns or features from the data.

Output Layer: The output layer is the final layer of the neural network. It **produces the network's prediction** based on information from hidden layers. A cost function relative to the real target is stored and used to improve the network



It can be much simpler than that

A **Feature selection algorithm** that recursively extracts a subset of candidate predictors, wrapped around a learner based on **decision tree** to predict heat waves.



Data-driven seasonal forecast of European heat waves

Candidate Drivers

Near-observational initial conditions

Large-scale (ERA5) Local-scale (ERA5 Land)

CO2 concentration (NASA)

Delayed effect

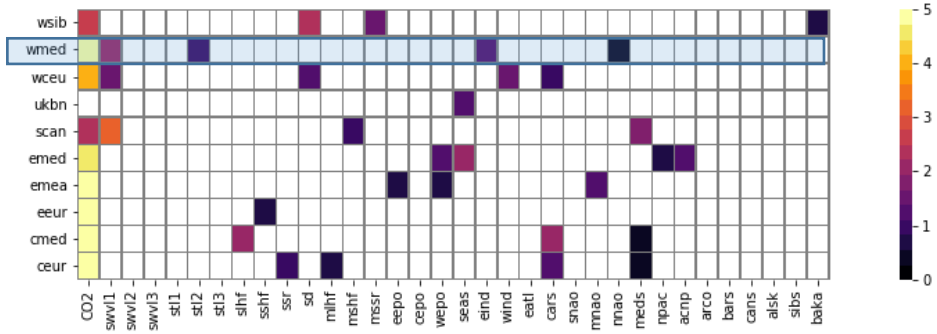
Tropical and extra-tropical SST anomalies; Sea Ice anomaly; etc.

Surface and deep soil water; soil temperature; surface radiation; etc.

Data-driven model trained on “observed” (ERA5) HWP

Seasonal forecast of heat waves (HWP)

Verifications



- The **global CO2 concentration is the main driver of heat waves** in west Medit
- **Surface soil moisture and soil temperature** also play an important role
- **SST in Eastern Indian ocean and Northern North Atlantic** also play a role

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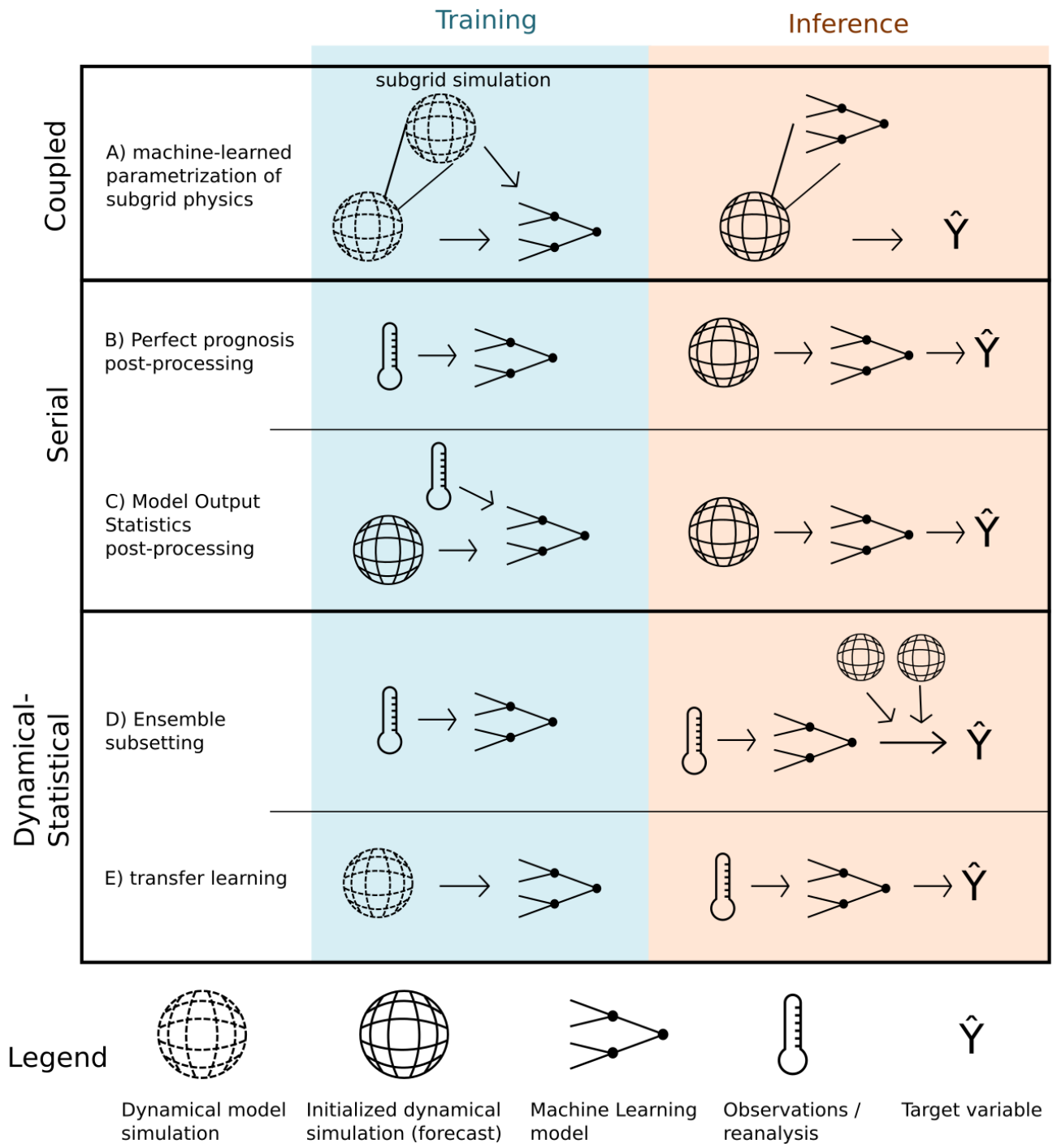
Materia et al., submitted

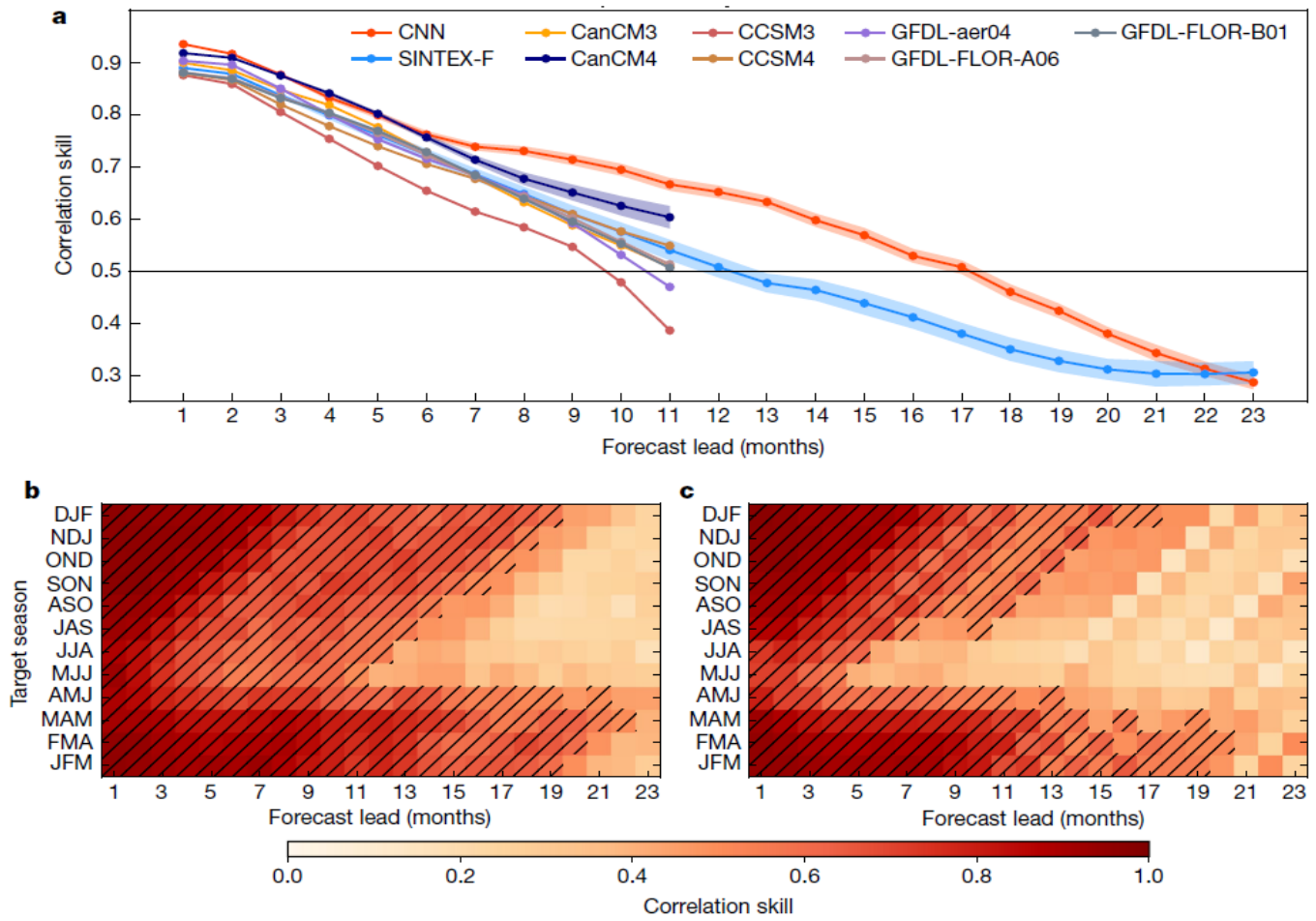
Hybrid models

Three main types:

- **Coupled**: AI can help improve the representation of processes coarsely represented in climate models.
- **Serial**: machine learning techniques to post-process climate model outputs. Used to bias-correct and/or downscale model outputs that suffer from inaccurate representations.
- **Dynamical statistical**: combine the prediction from a dynamical model, with that of an empirical, purely data driven approach, where the data-approaches as well as the way to combine prediction vary.



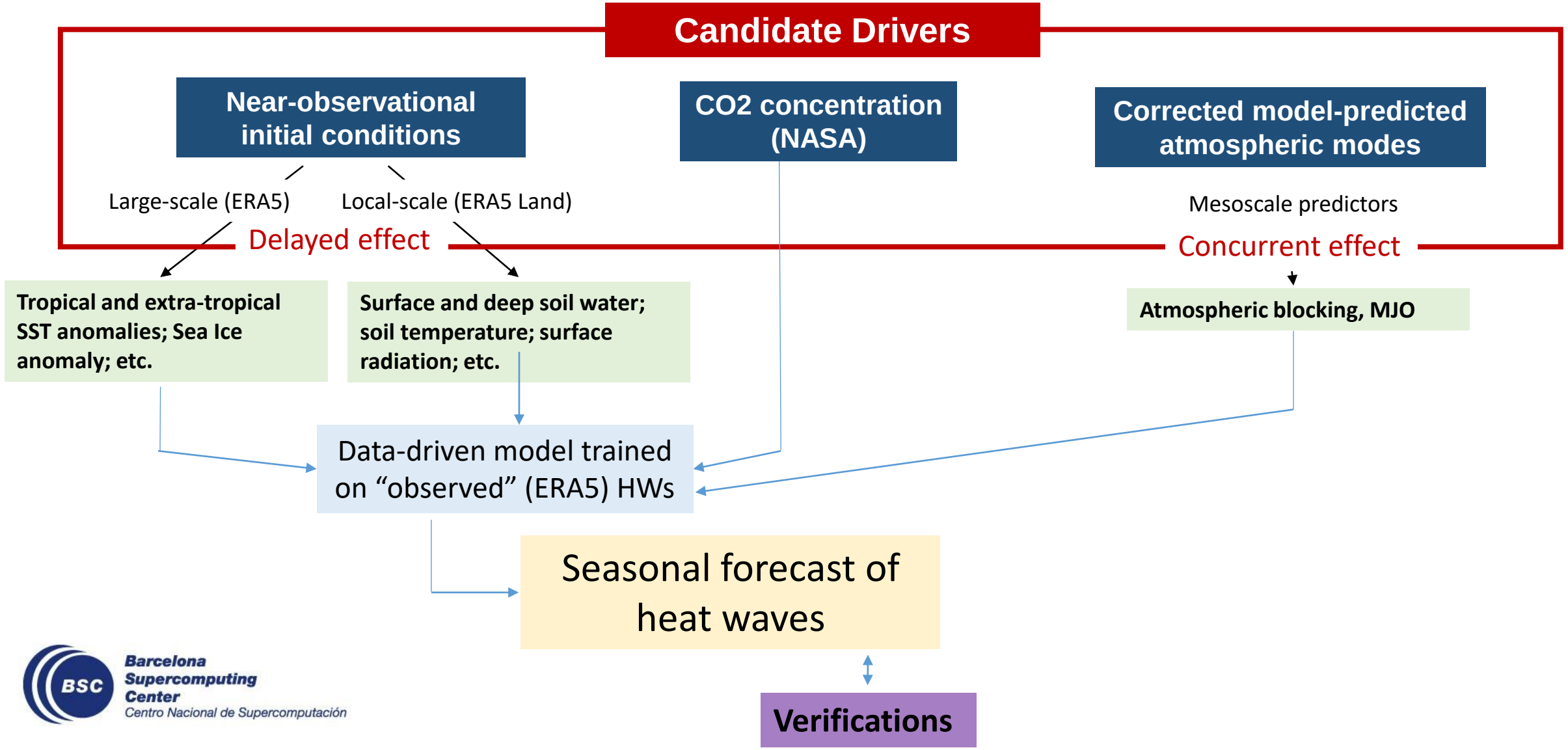
Multi-year predictions of ENSO



A **neural network** trained over climate simulations and reanalyses has demonstrated the ability to skilfully **predict ENSO** up to almost two years in advance, particularly **improving the spring barrier** and also **the zonal distribution of SSTs**

Ham et al. 2019

Selection of drivers of seasonal predictability and Seasonal prediction of heat waves in Europe



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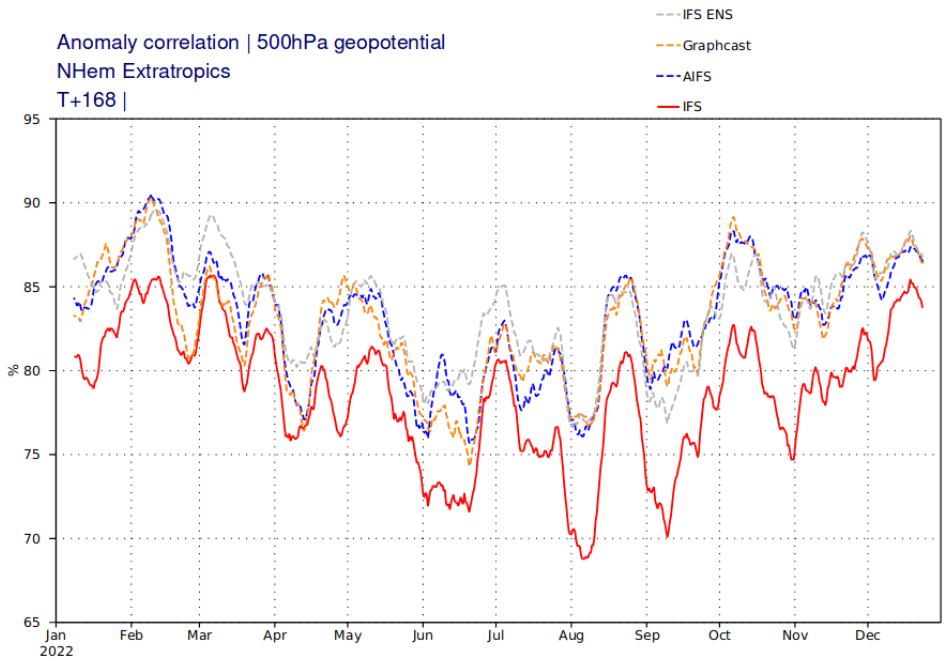
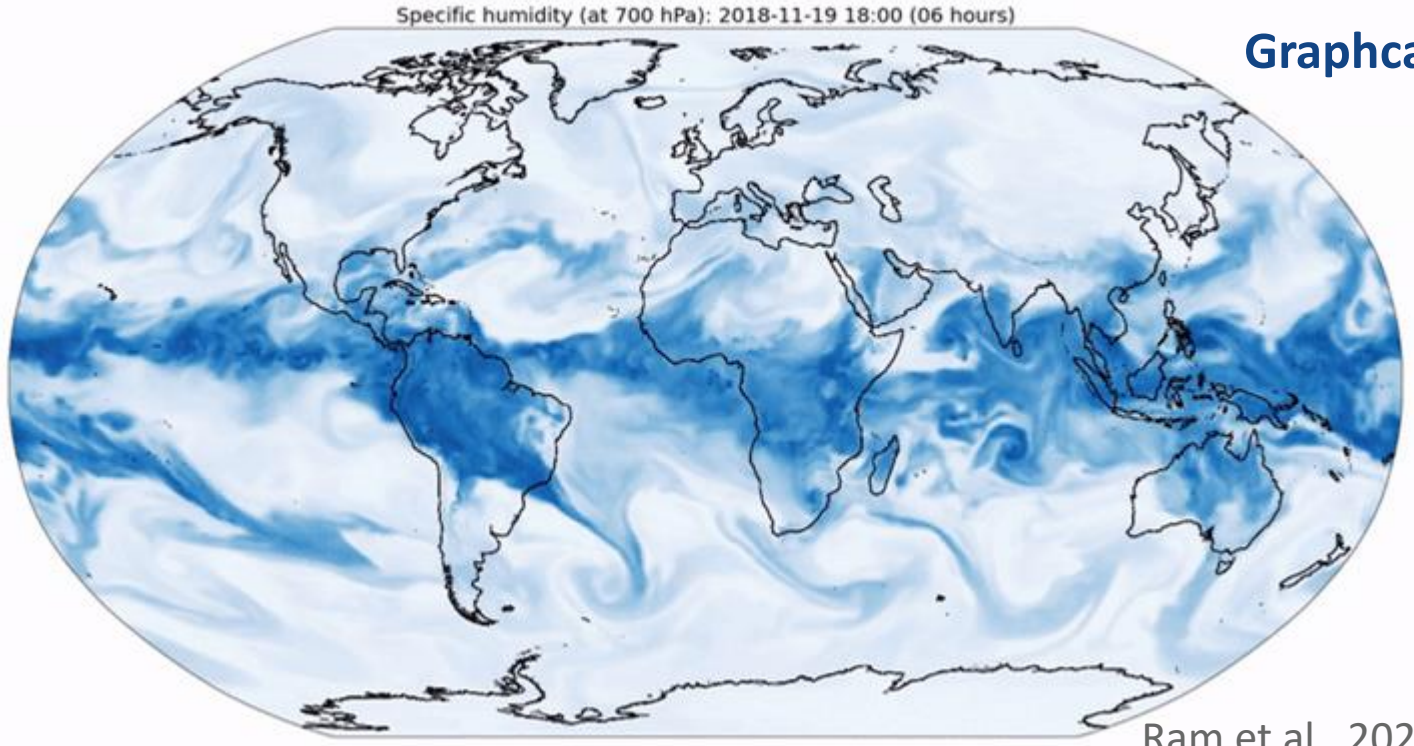
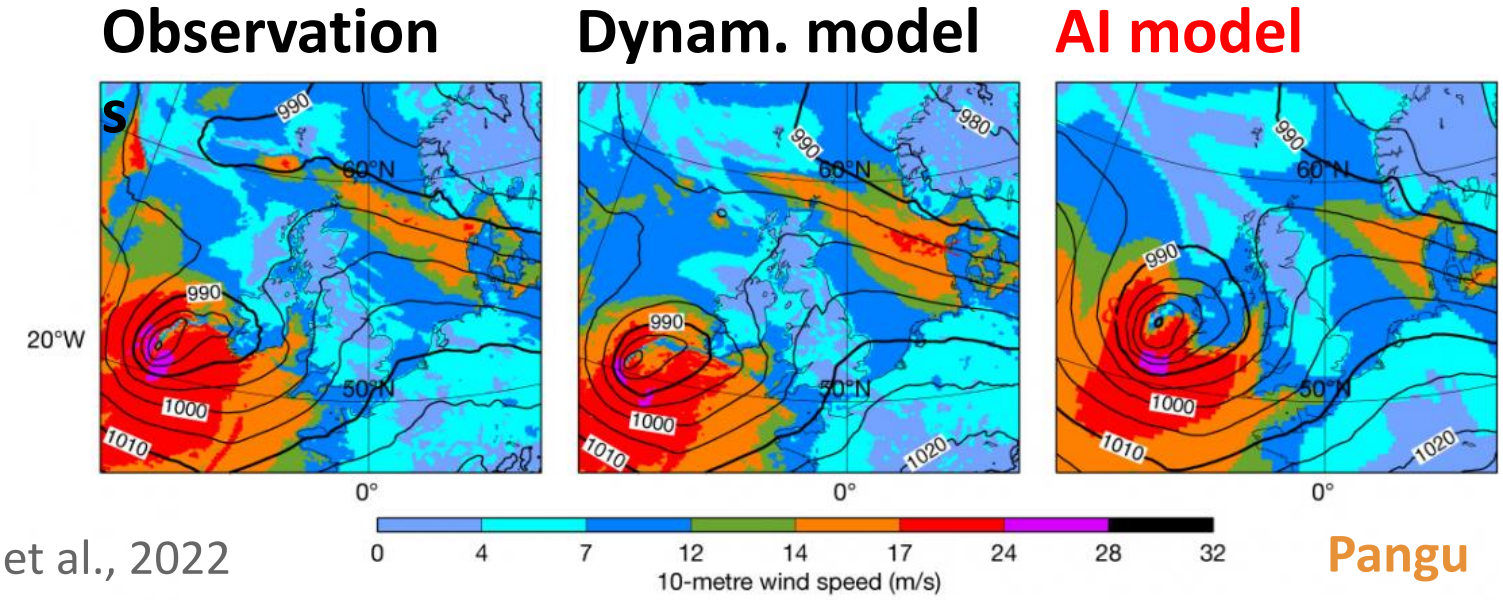
Models based on AI are totally competitive with dynamical ones



AIFS Lang et al., 2024



Graphcast Ram et al., 2023



Bi et al., 2022 **Pangu**

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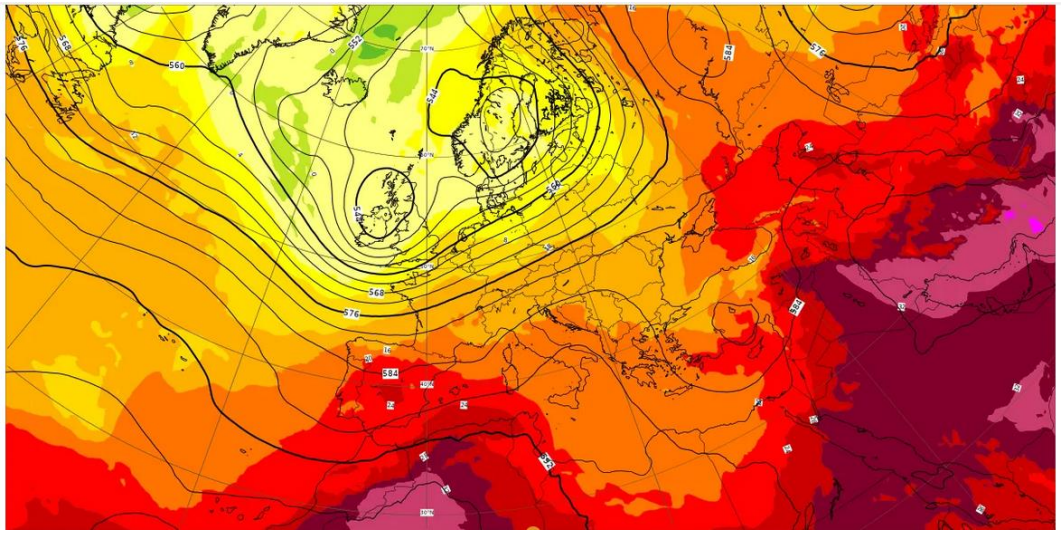
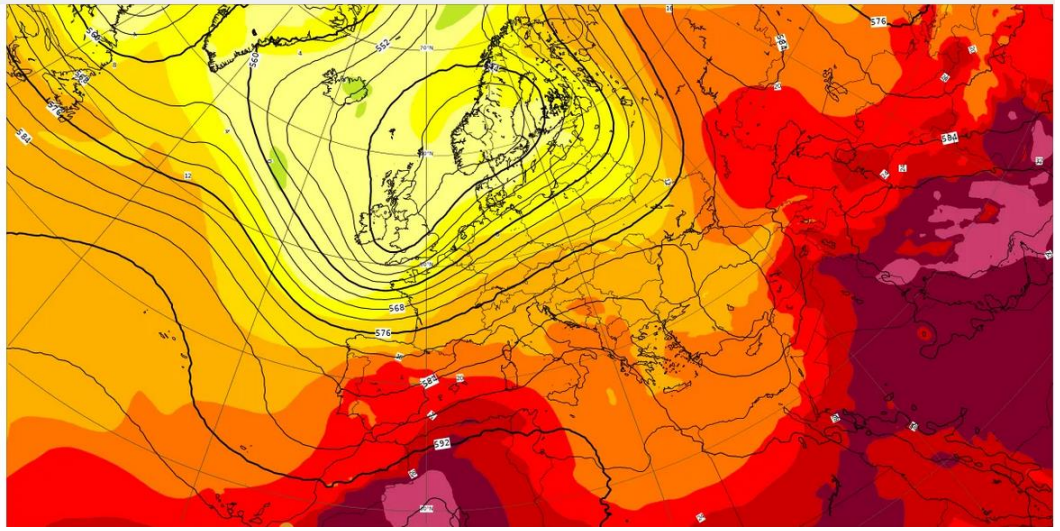
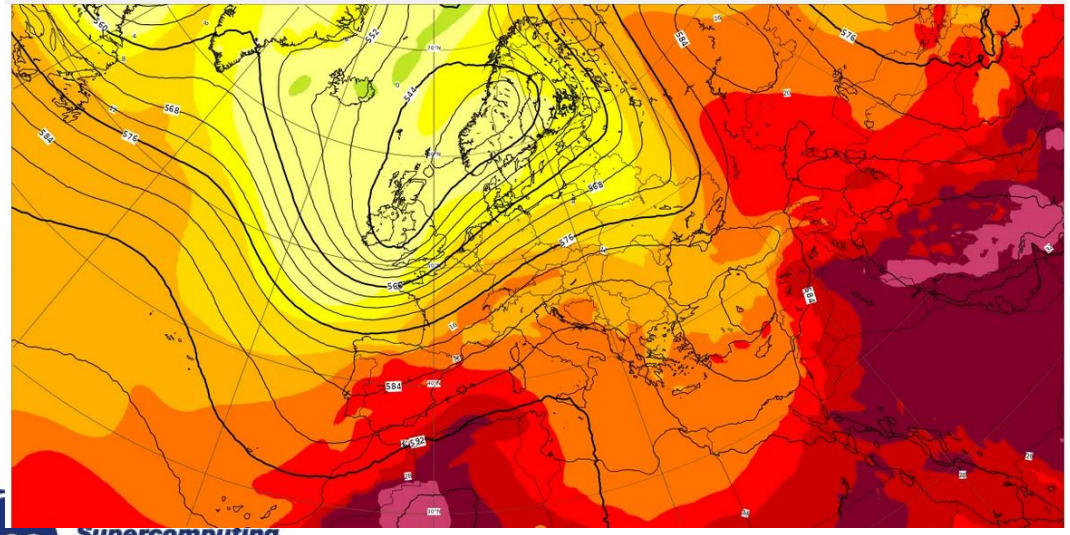
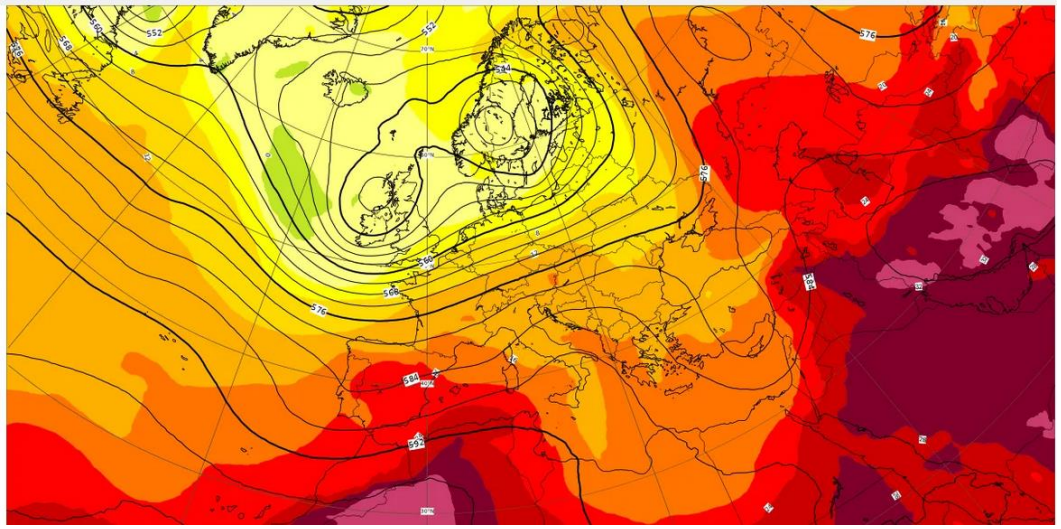
Prediction for Saturday 05/07 0z

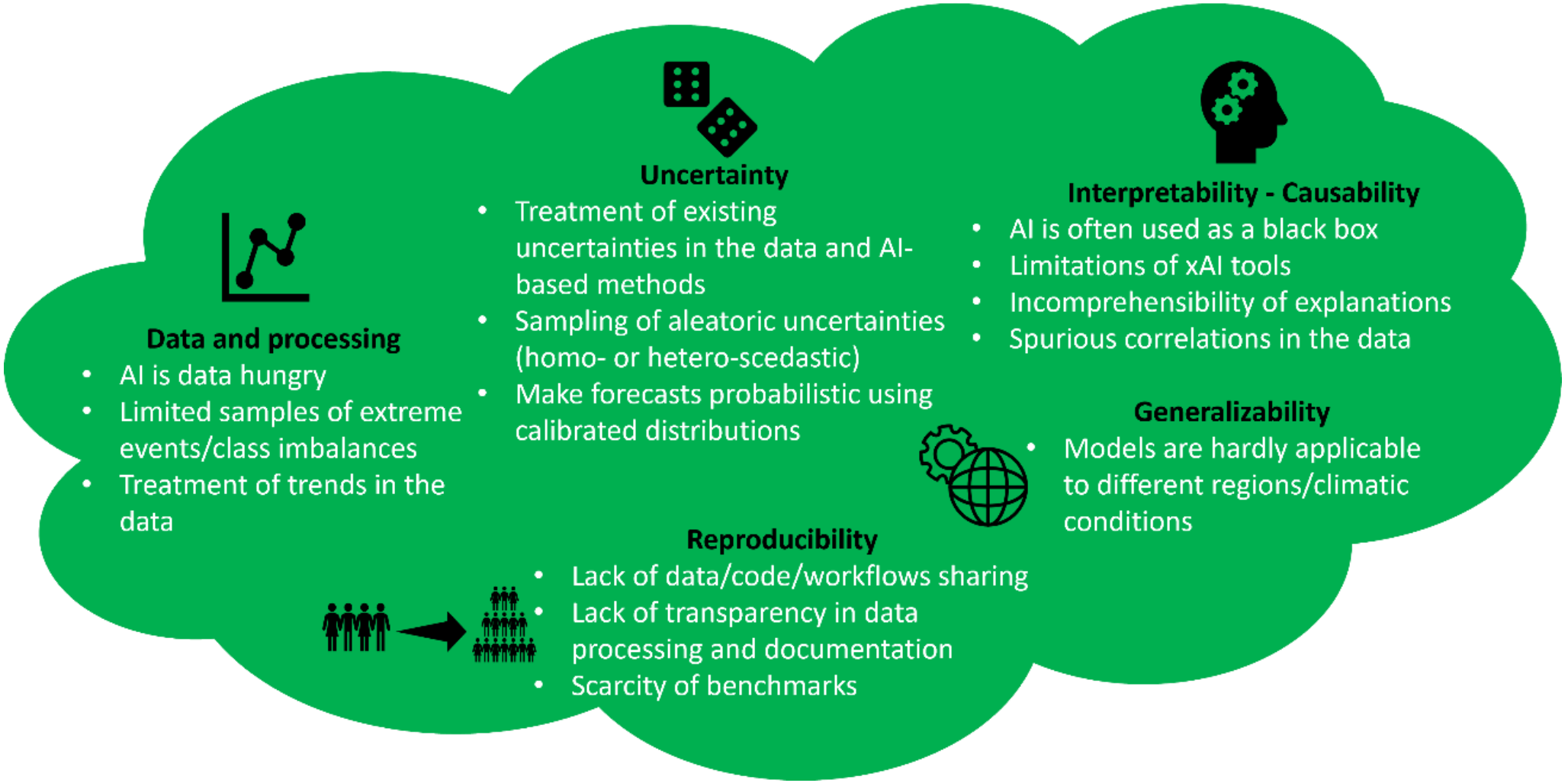




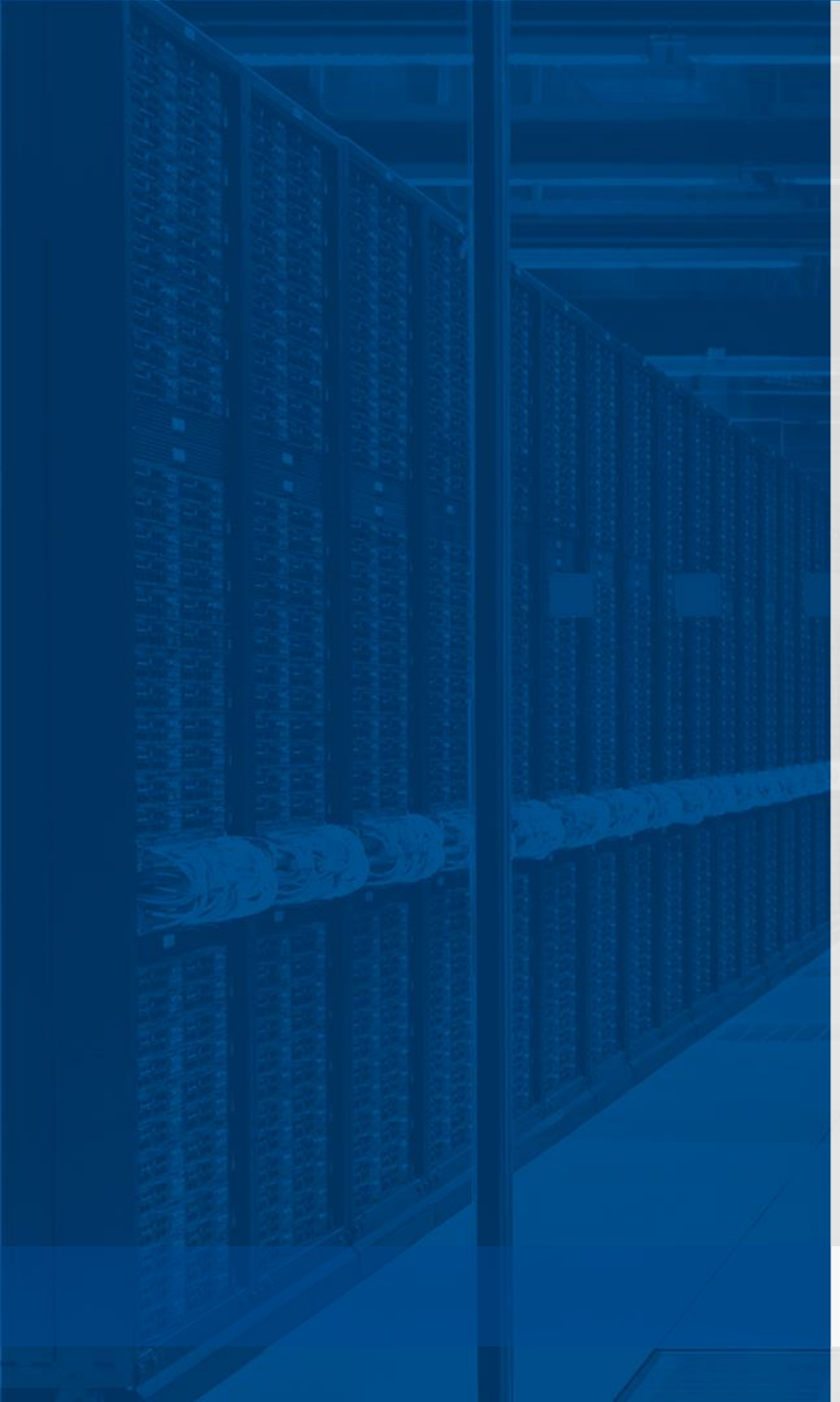




Challenges in AI-based Prediction of Climate Extremes



Materia et al., 2024



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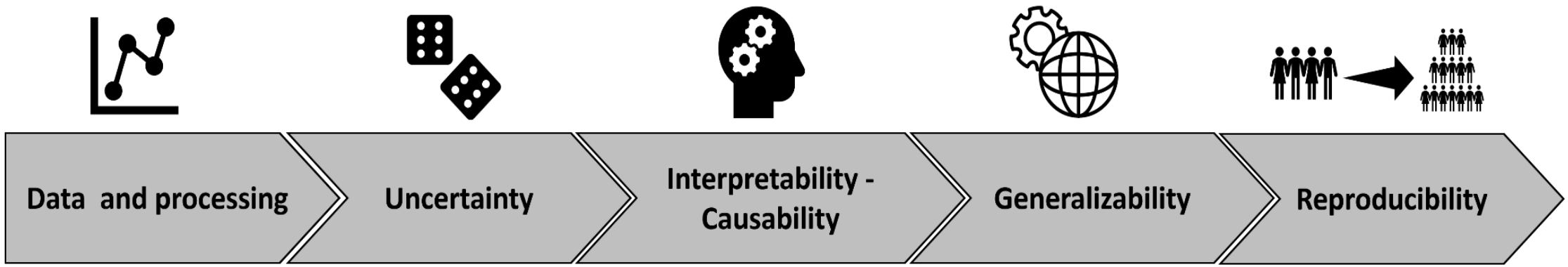
Blending empirical and dynamical information in forecasting

stefano.materia@bsc.es

Perspectives and opportunities for AI-based Prediction of Climate Extremes



- Transfer learning and fine tuning to increase sample for longer forecast times
- Resample training datasets/cluster the abundant class
- Prediction of compound extremes

- Utilize Probabilistic Machine Learning:
  - Dropout MC
  - Multiple random seeds
  - Bayesian models
- Data and physics learning, deep learning + data assimilation

- Inherently interpretable AI-models
- Develop xAI best practices and tools that account for interdependent features
- Explore causability of AI when combined with established causal discovery tools

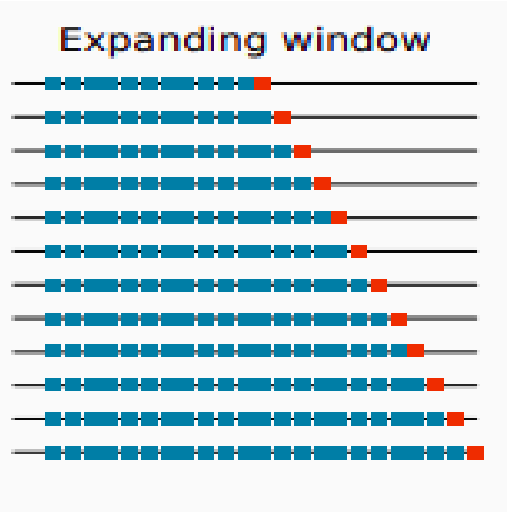
- Build physics-guided AI models
- Transfer learning and domain adaptation techniques
- Build hybrid prediction structures that combine AI and Earth system models

- Open science protocols in publishing
- Build wider benchmark datasets
- Introduce platforms that ensure reproducibility (e.g. CWFR)

Materia et al., 2024

Forecast evaluation

- The model is trained 19 more times, each time up to a year before the event to test - (1950-2020 to test the 2021 heat waves, etc.).
- The parameters to be used are those from the 2022 training, but the feature are re-selected all the times.
- In this way I will have 20 test years to compare with dynamical seasonal forecasts.



West Med