



Funded by the
European Union



**Weather
Generator**



The WeatherGenerator

Large scale machine-learning for Earth
System modeling

Ilaria Luise
European Center for Medium-Range Weather Forecasts

Introduction



Exciting times for data driven weather modelling



25/02/2025

AIFS OPERATIONAL

Latest forecast: AIFS Single: Mean sea level pressure and 850 hPa wind speed

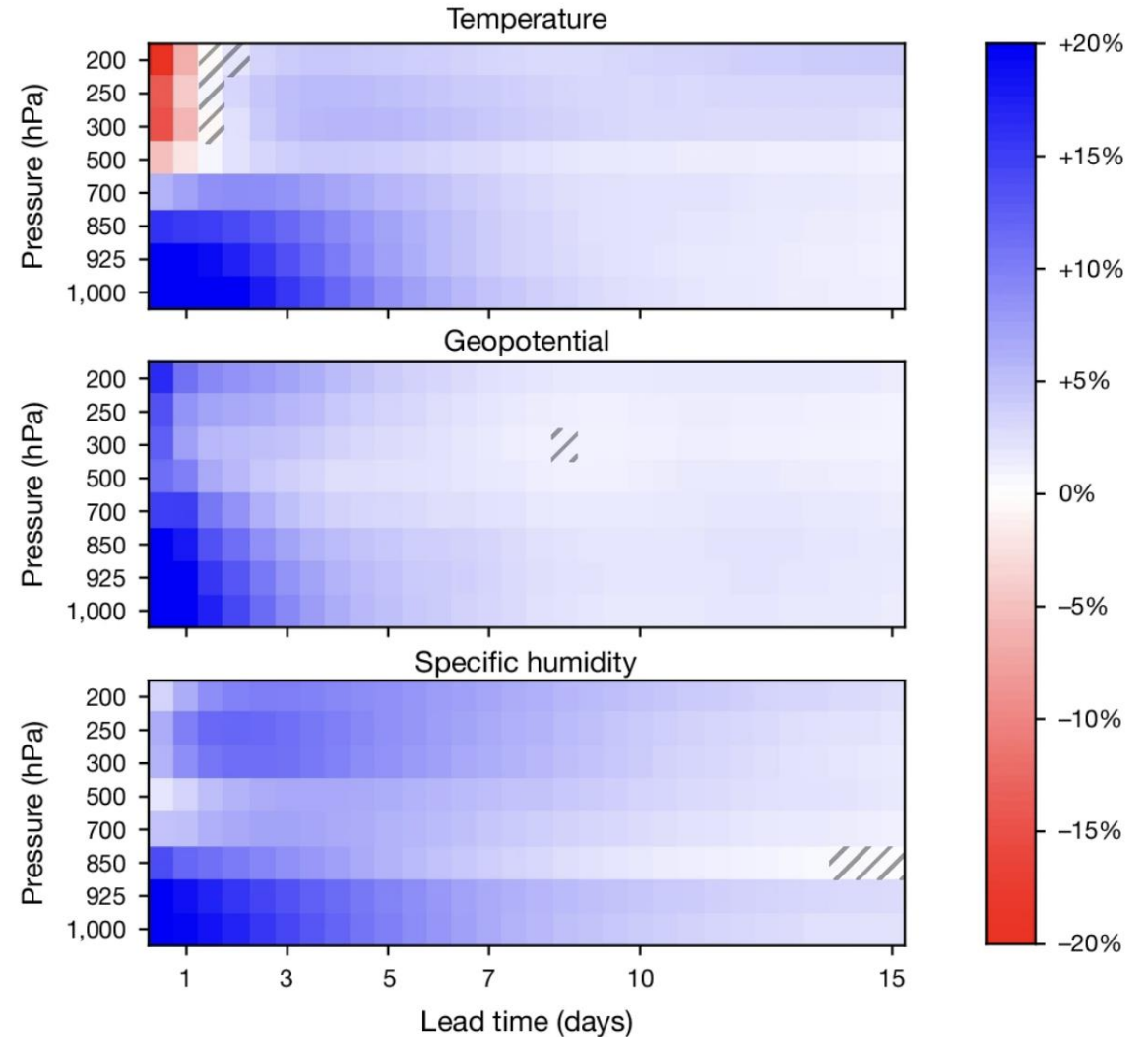
Latest forecast: AIFS Single: 500 hPa geopotential height and 850 hPa temperature

Latest forecast: AIFS Single: 100 m wind and mean sea level pressure

Wind speeds near the surface are roughly proportional to the distance between isobars so closely packed isobars mean strong surface winds...

The 850 hPa level is usually just above the boundary layer and at this level the day-night variation in temperature is generally negligible...

These charts show surface pressure patterns. Areas of high pressure (anticyclones) are usually associated with settled weather...

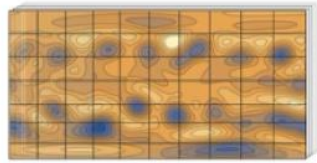
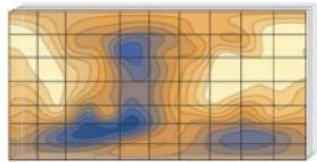
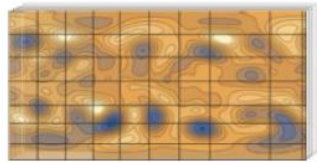
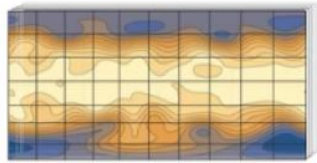


GenCast: [Probabilistic weather forecasting with machine learning](#), Nature 2024

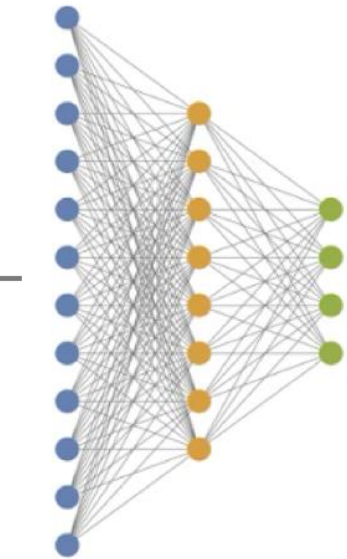
Current data driven models (the majority)



ERA5 reanalysis

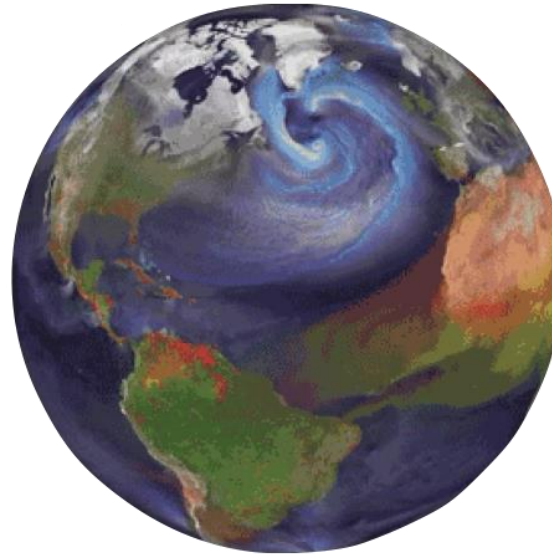


50 TB

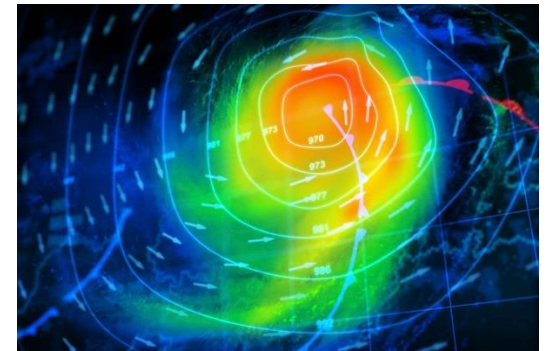


large scale
machine learning

Model trained and
tested for forecasting

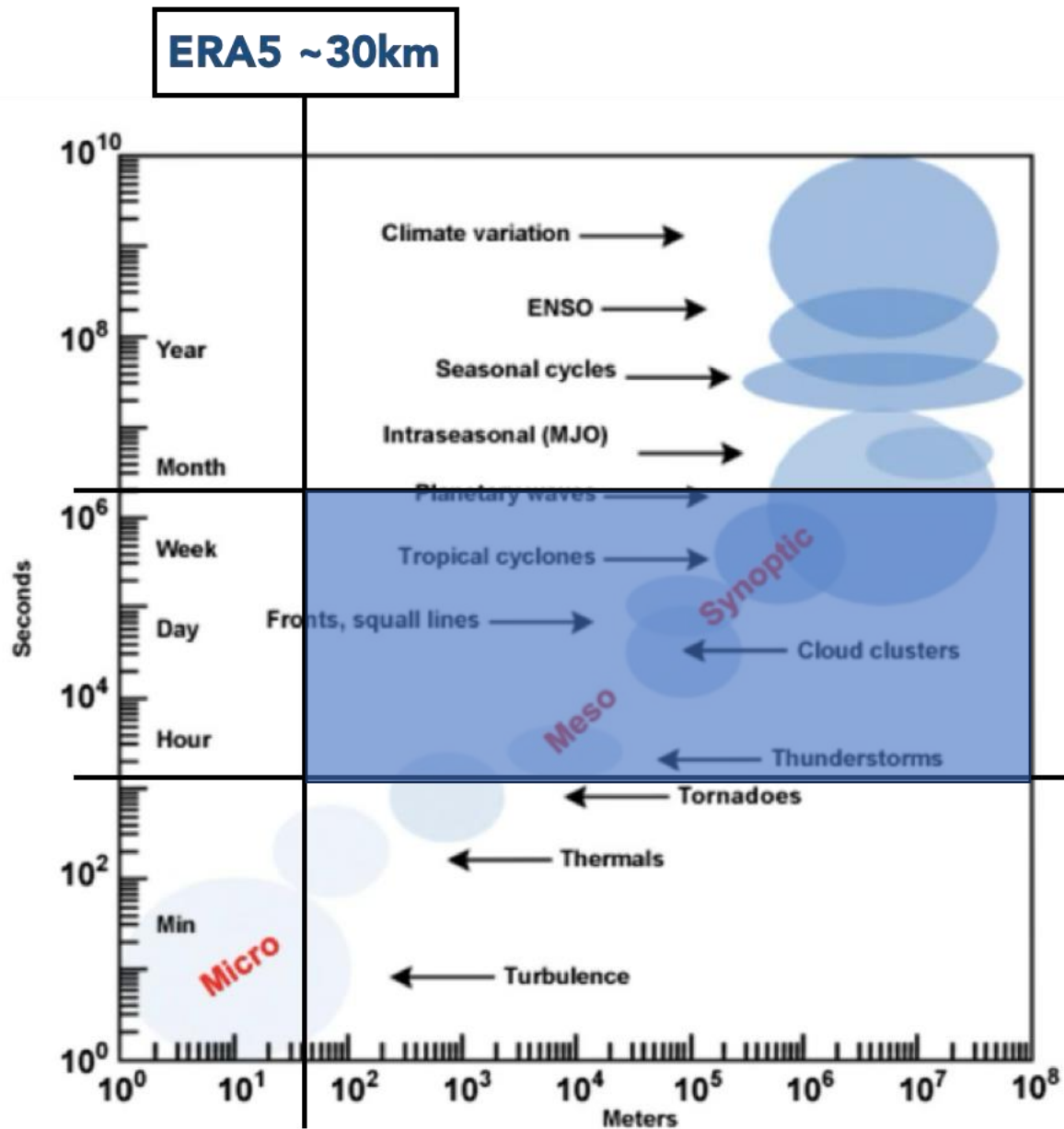


Model
*given by the trained
neural network*



- Medium range forecasting
- Hurricane tracking
- ...

But..



We are spanning “only” part
of the phase space:
still far from a seamless ML
approach

.. and

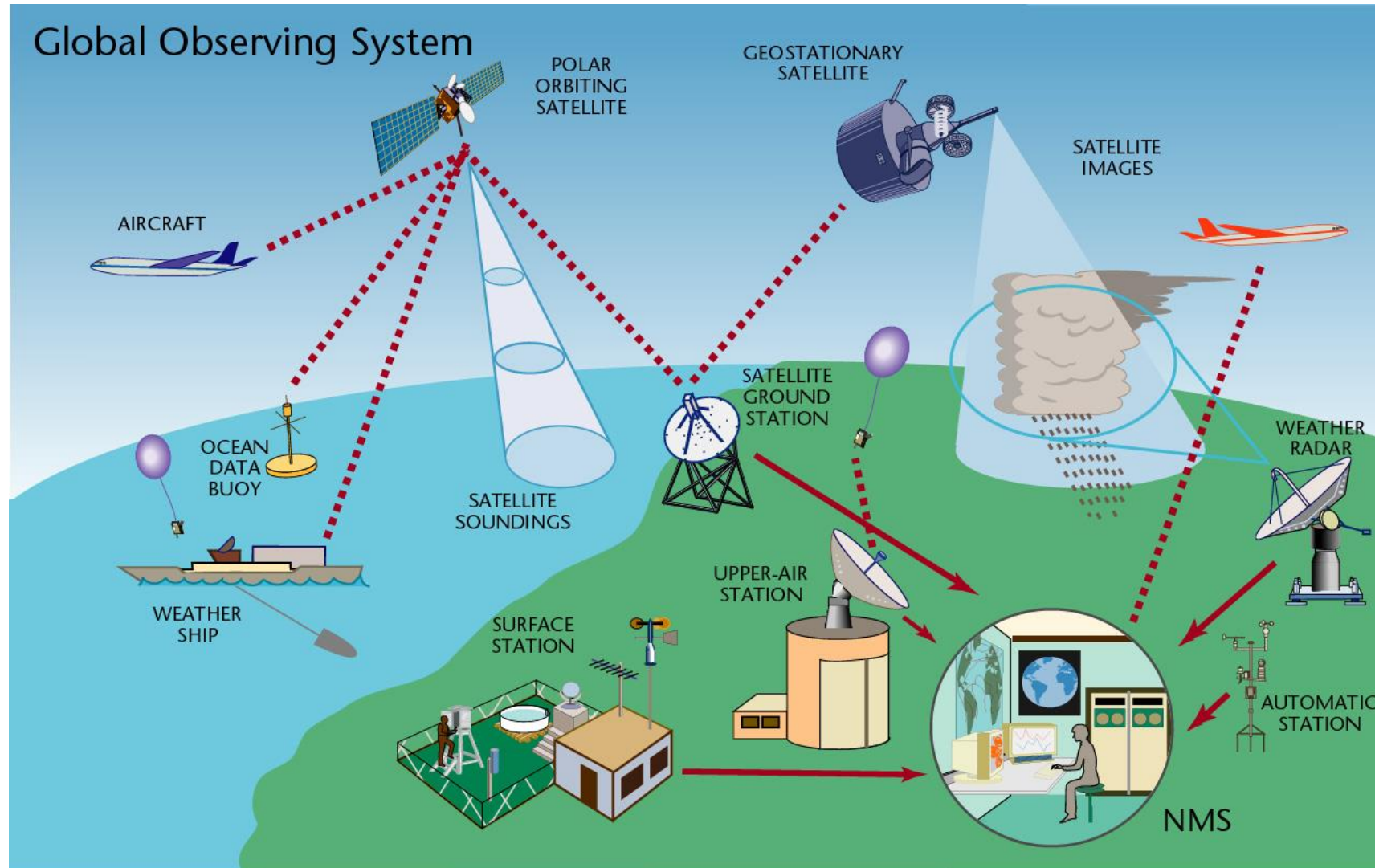




Can we go beyond?

Towards a multi-resolution data driven model for Earth System science

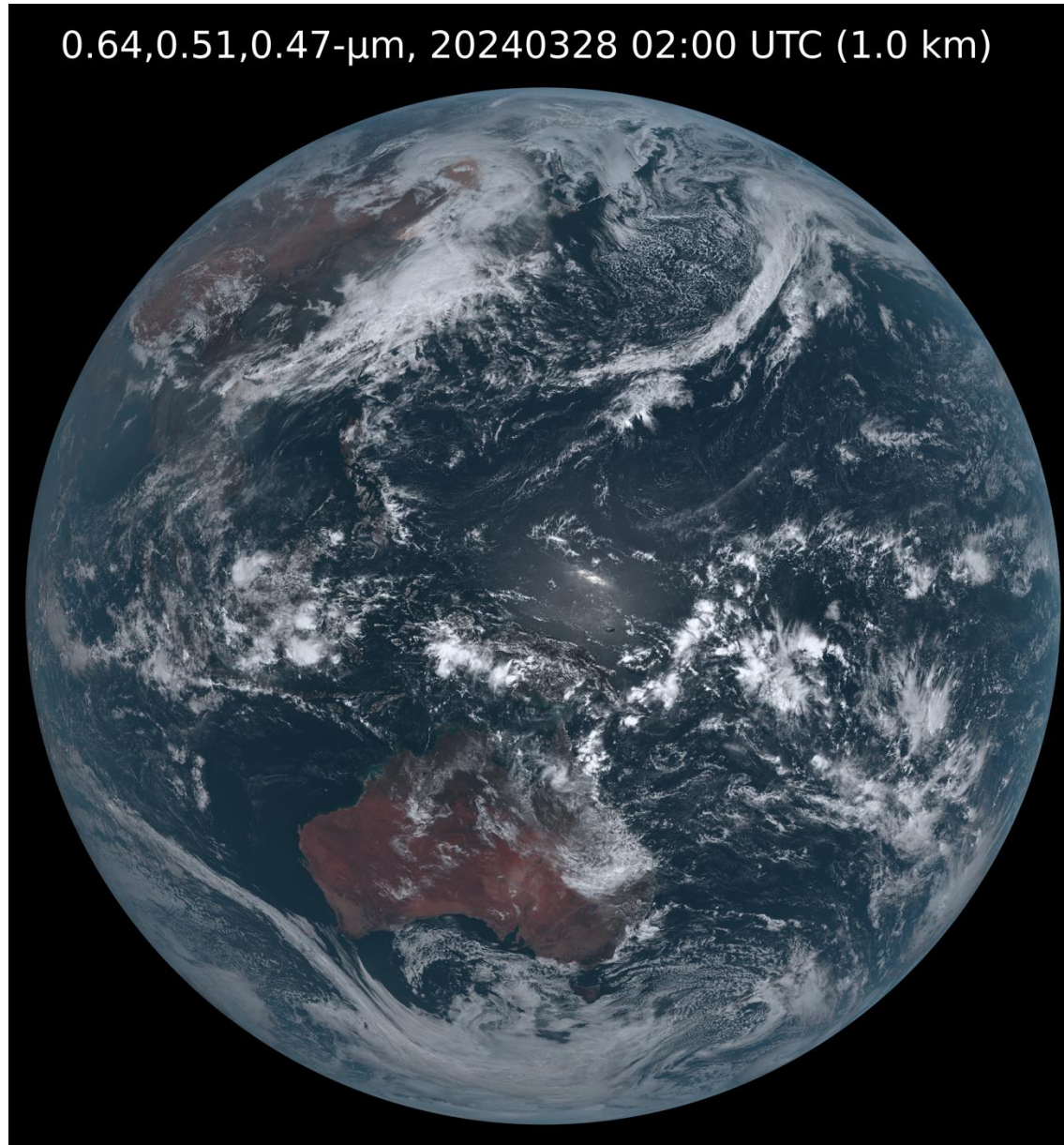
We have lots of data at different scales



We have lots of data at different scales



Example:
Himawari GEO

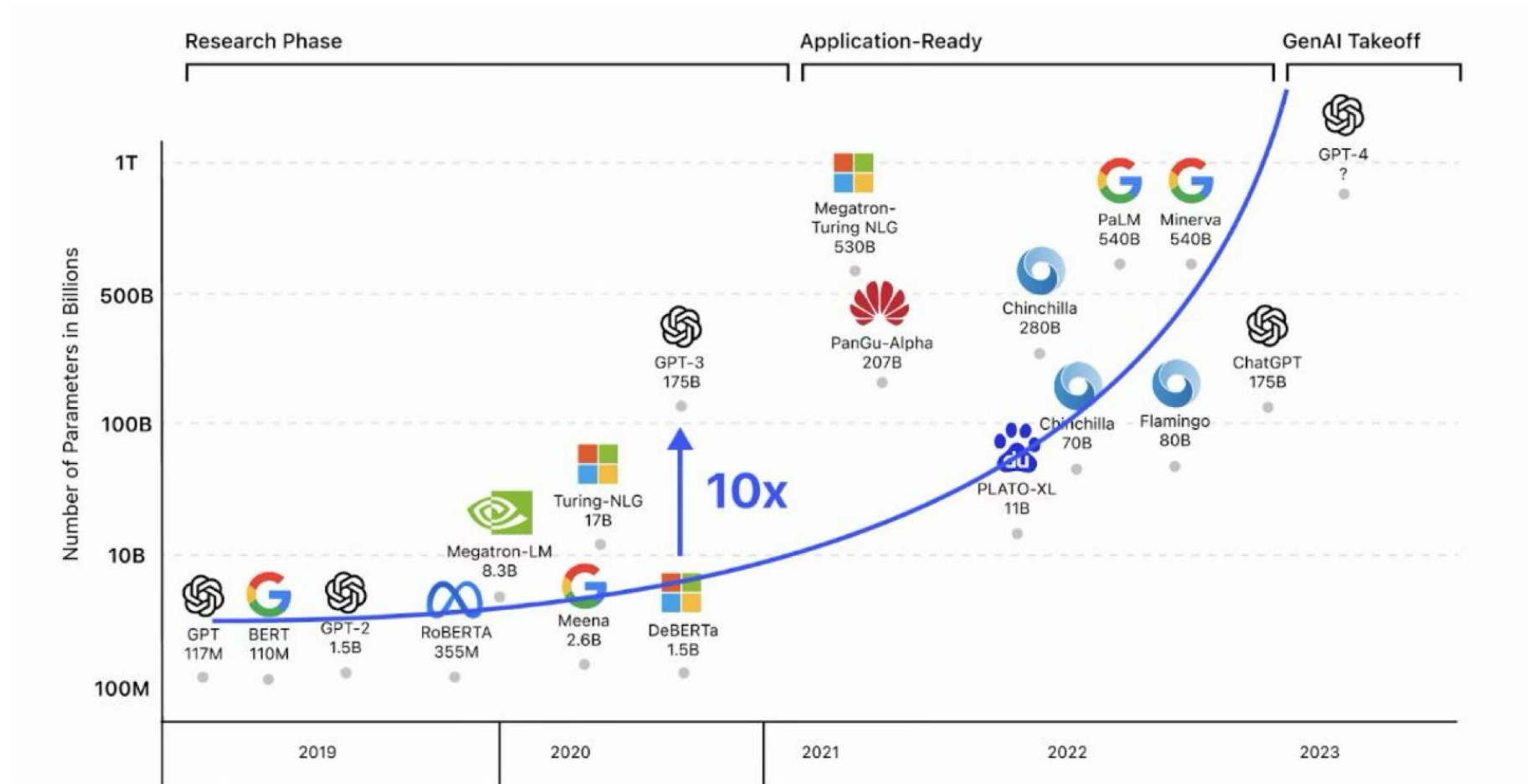


- Spatial resolution: 500m-2km
- Time resolution: 10 minutes

.. and we have the technology to combine them



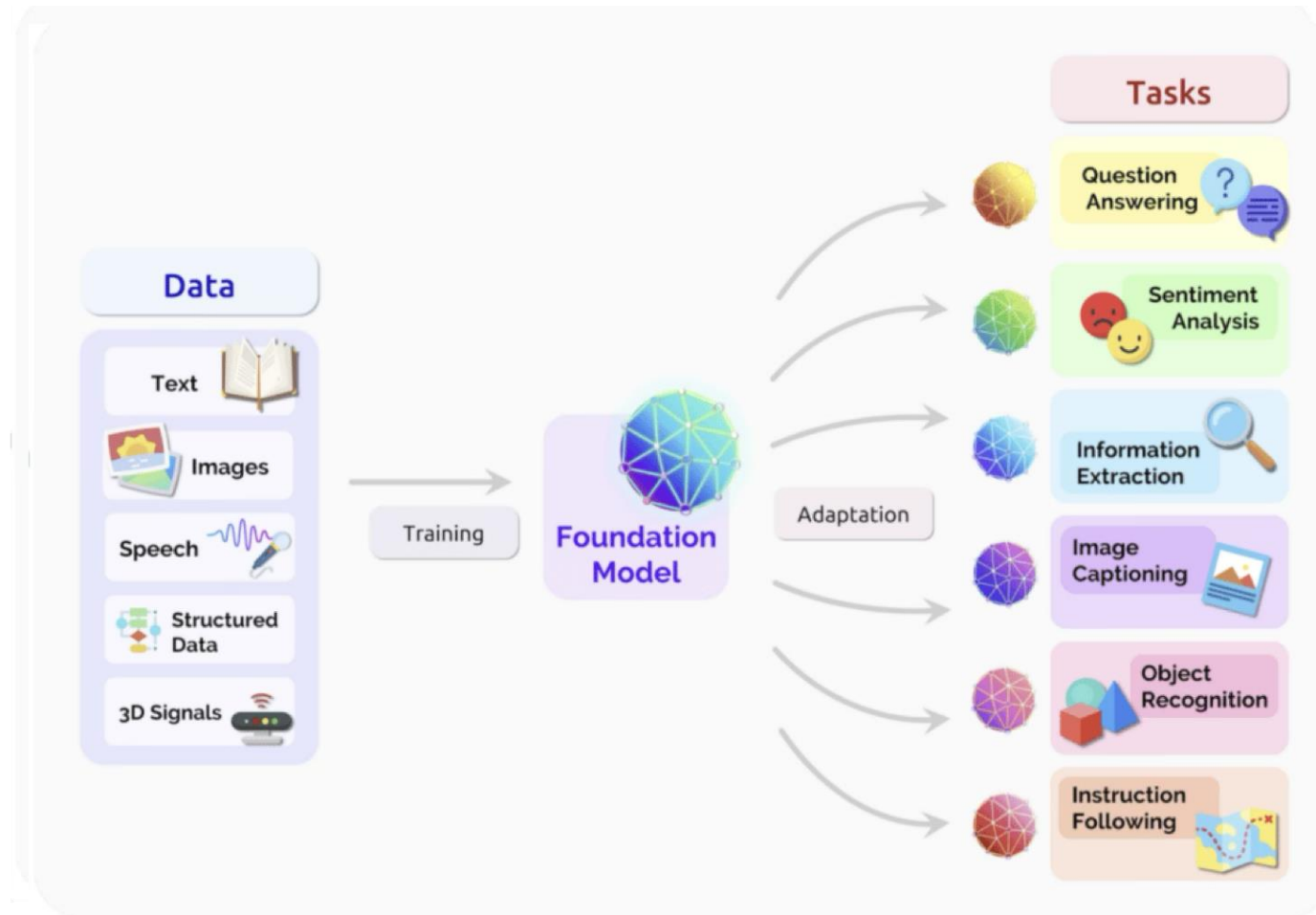
- Models that are **multi-modal**: couple text, video, images in the same feature space
- Models with trillions of parameters that can fulfill **multiple-tasks**



.. and we have the technology to combine them



- Models that are **multi-modal**: couple text, video, images in the same feature space
- Models with trillions of parameters that can fulfill **multiple-tasks**



Do we have *enough* data?



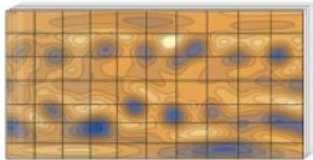
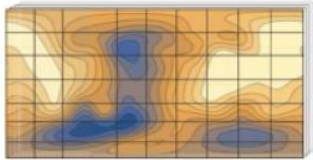
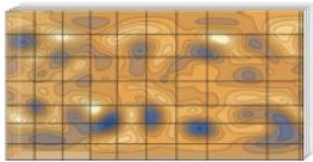
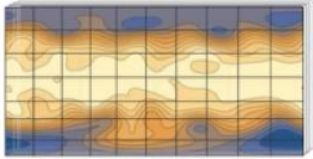
Do we have enough data?

- ✓ For parametrization emulation – Yes, but pointless.
- ✓ For global medium-range weather predictions – Yes, we have ERA.
- ? For longer predictability horizons – The more data, the longer the horizon – Butterfly effect?
- ? For seasonal predictions – Depends on the question and the approach.
- ? For global data assimilation – To be seen.
- ✓ For land modelling – Yes.
- ✓ For sea-ice modelling – Yes.
- ✓ For the ocean – Yes for the surface, no for the deep ocean.
- ✓ For global atmospheric chemistry – Yes to emulate, no to become better than physical models.
- ✗ For climate simulations to measure climate sensitivity – No.
- ✗ For studies of climate tipping points – No.
- ✓ For extreme weather events in a future climate – Yes, in combination with physical models.
- ✓ For local down-scaling – Yes for 2mT. Partly for precipitation. Data of physical models for 3D.
- ✓ For prediction of grey swan events – Yes, when using data of physical models.

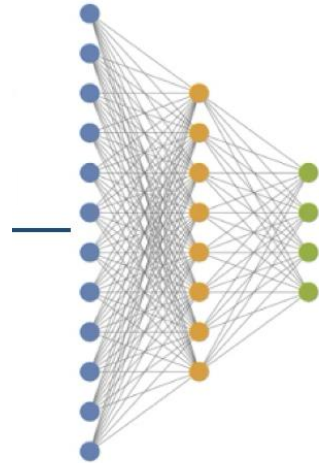
Current data driven models (the majority)



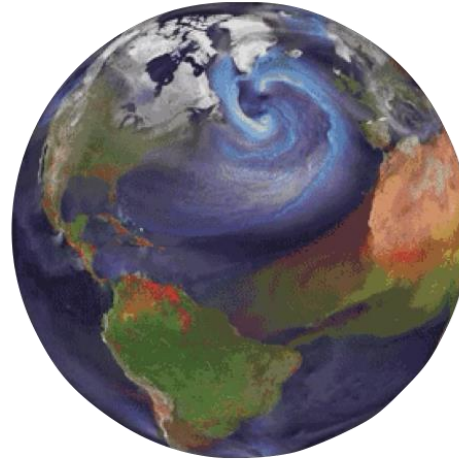
ERA5 reanalysis



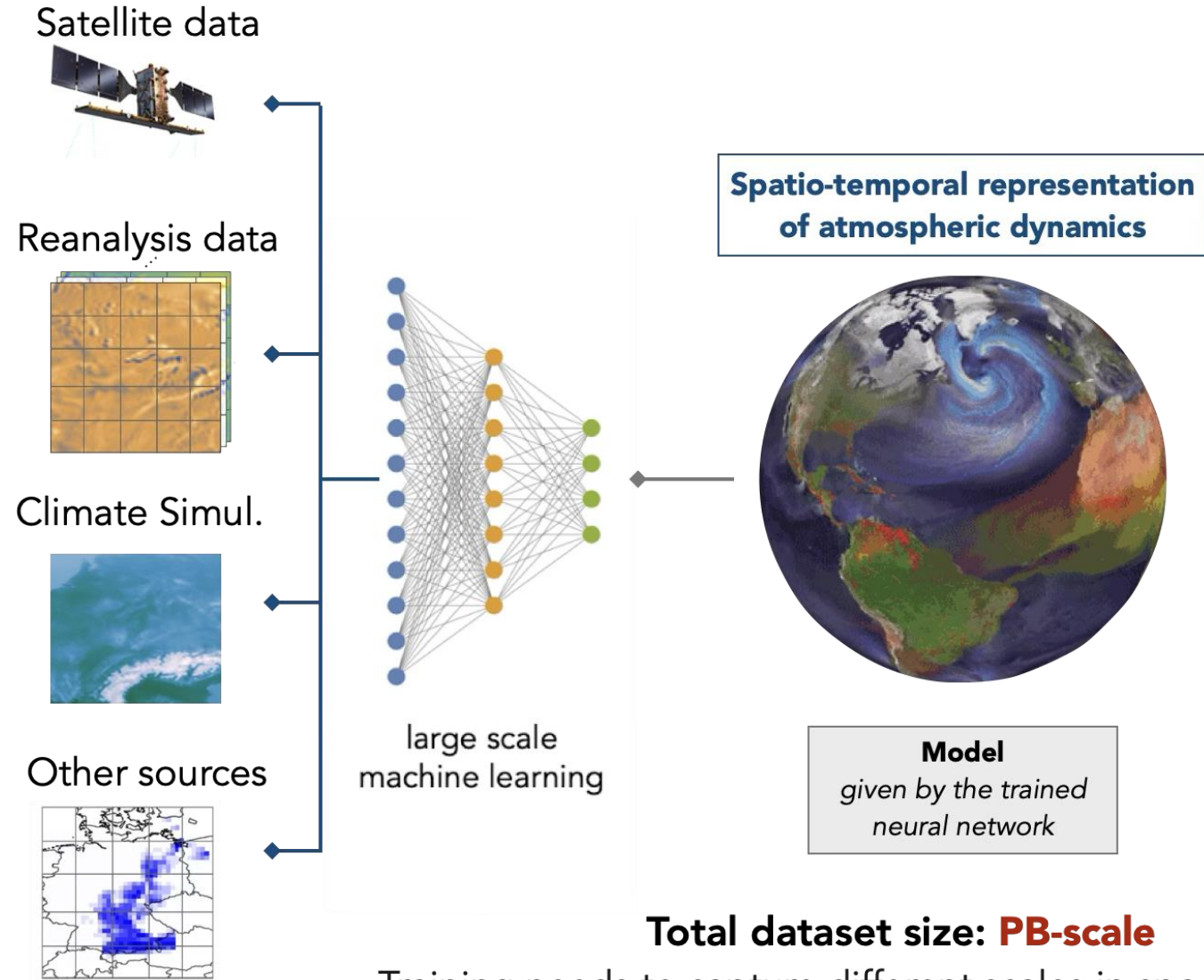
50 TB



Model trained and tested for forecasting



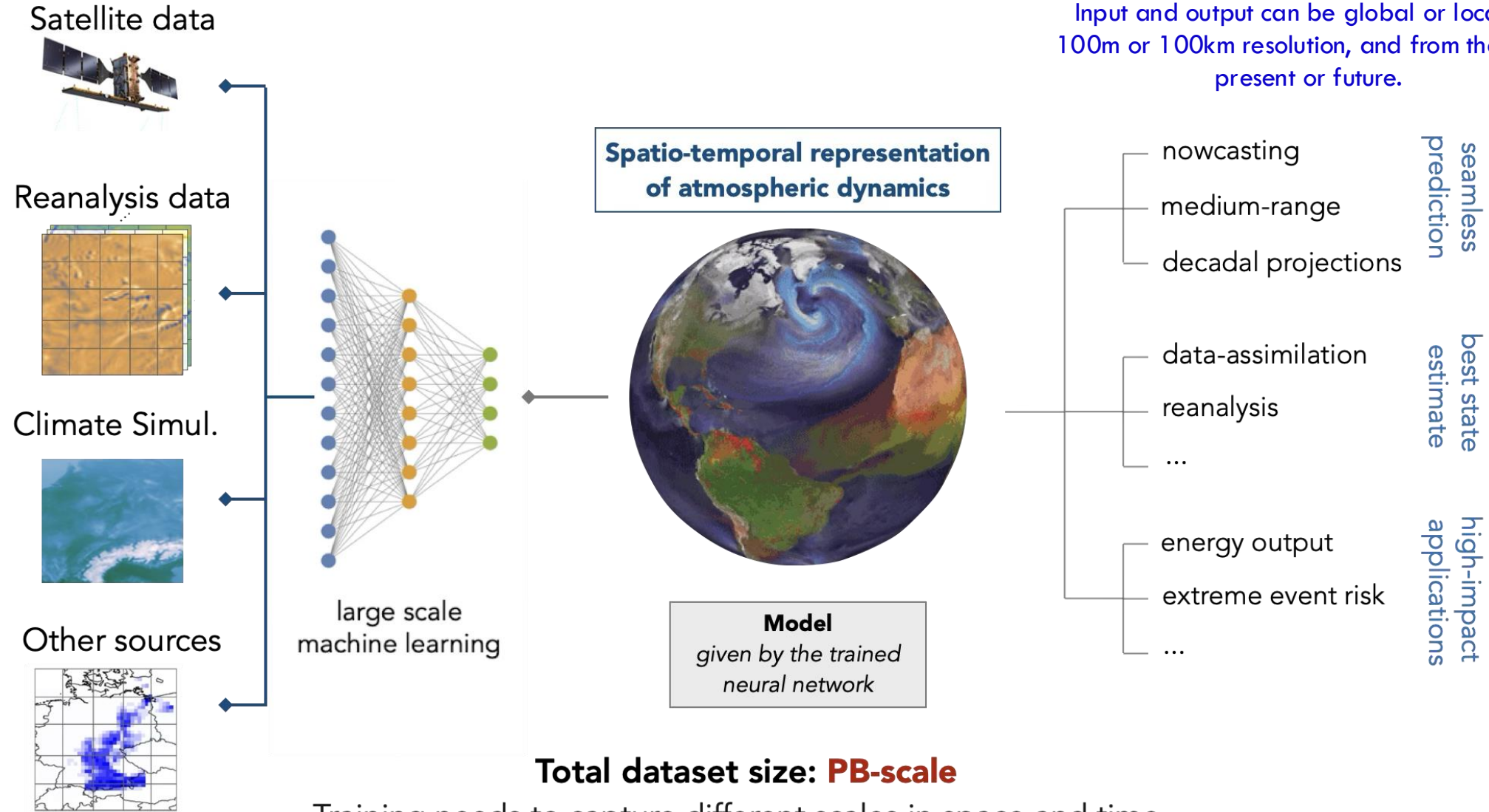
The WeatherGenerator in a nutshell



Total dataset size: PB-scale

Training needs to capture different scales in space and time

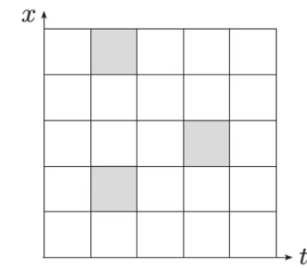
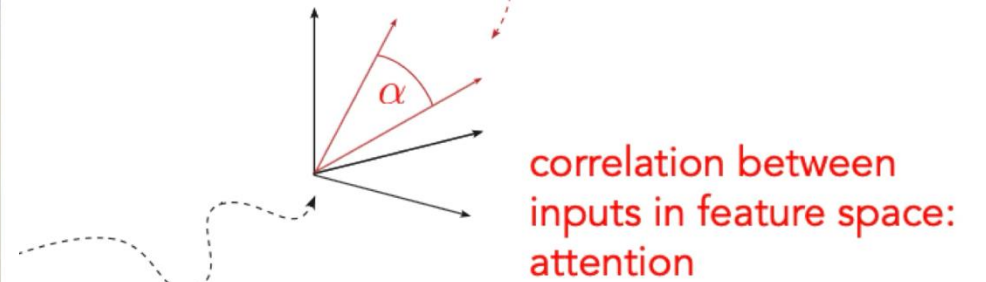
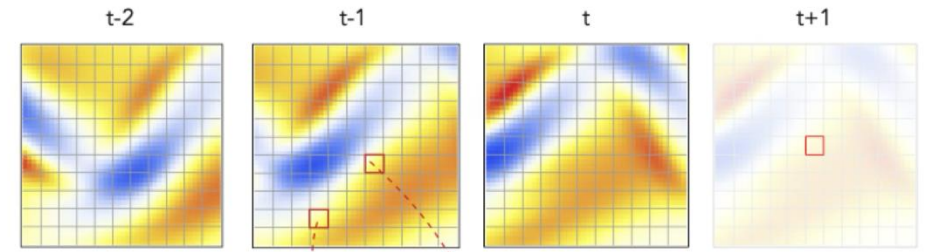
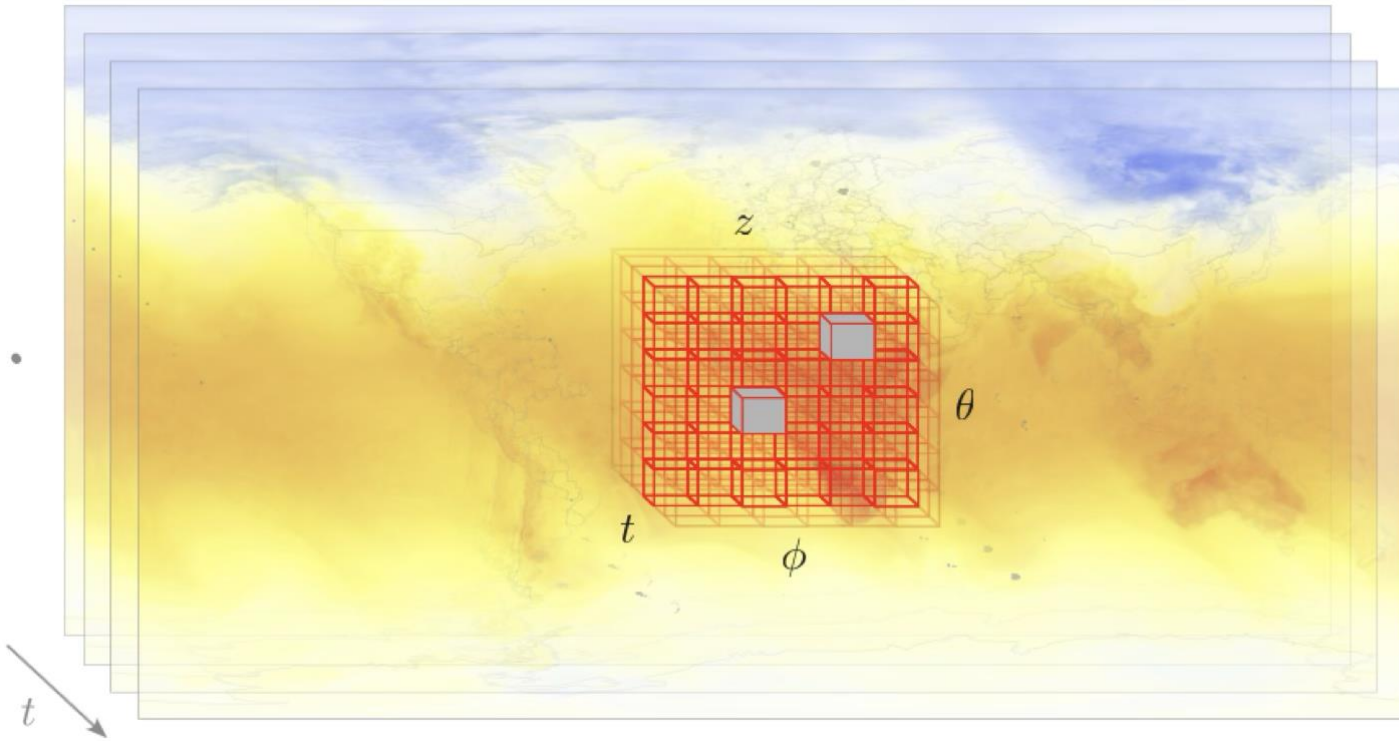
The WeatherGenerator in a nutshell



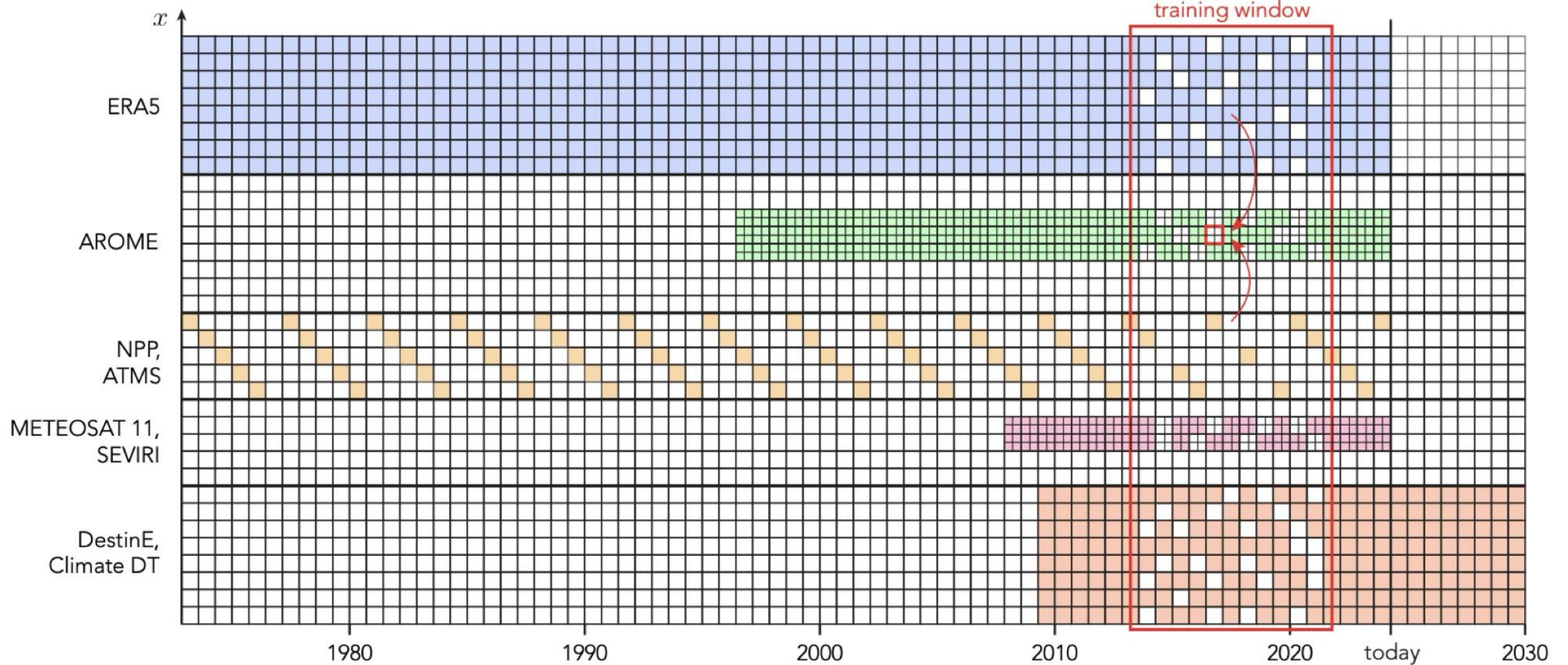
Key ingredient: Representation learning



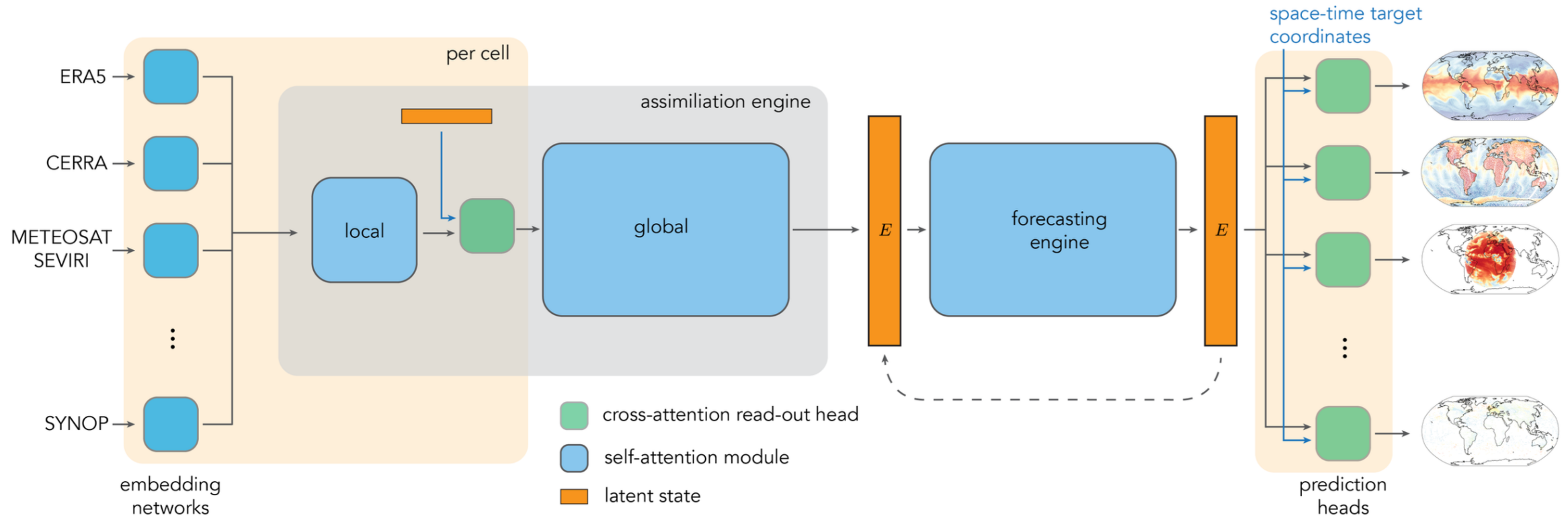
Use transformers to encode the information in feature space



How to combine multiple time scales scales?



How to deal with different resolutions?

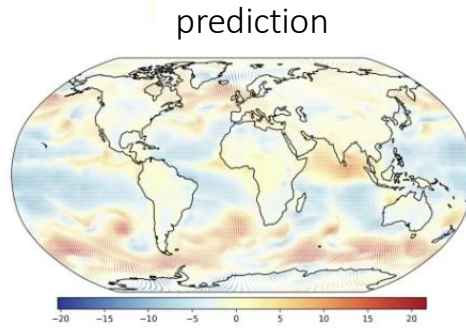
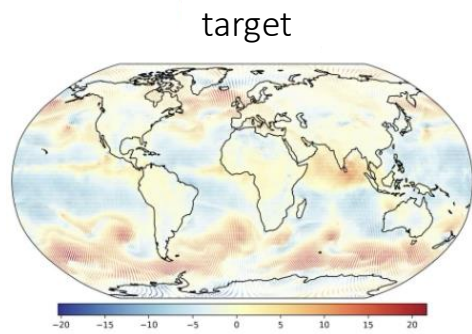


E global latent Earth system state

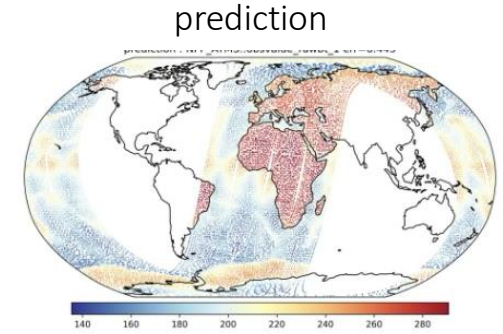
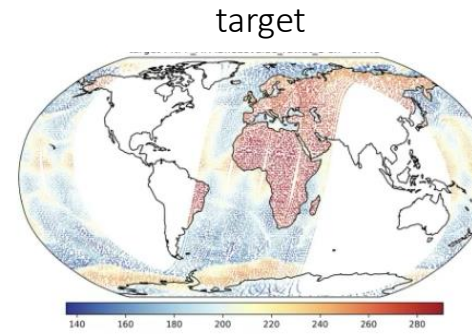
Where do we stand?



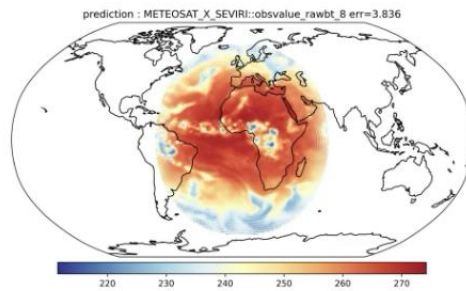
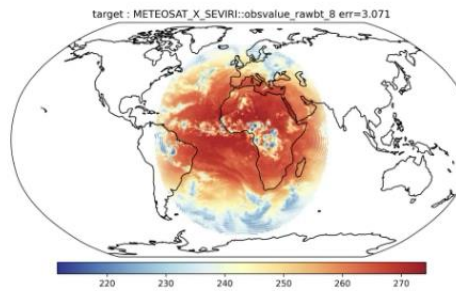
We do have the prototype of a model that trains on multiple datasets



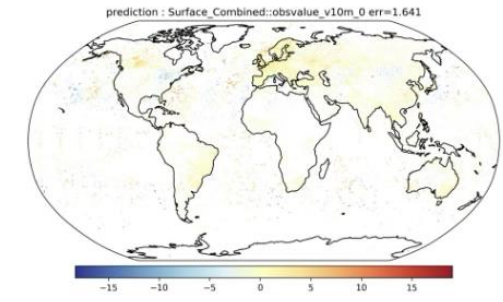
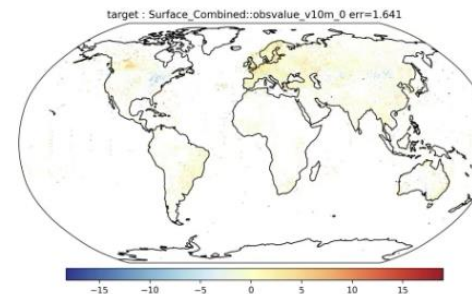
ICO, 10u



NPP, ATMS
ch1



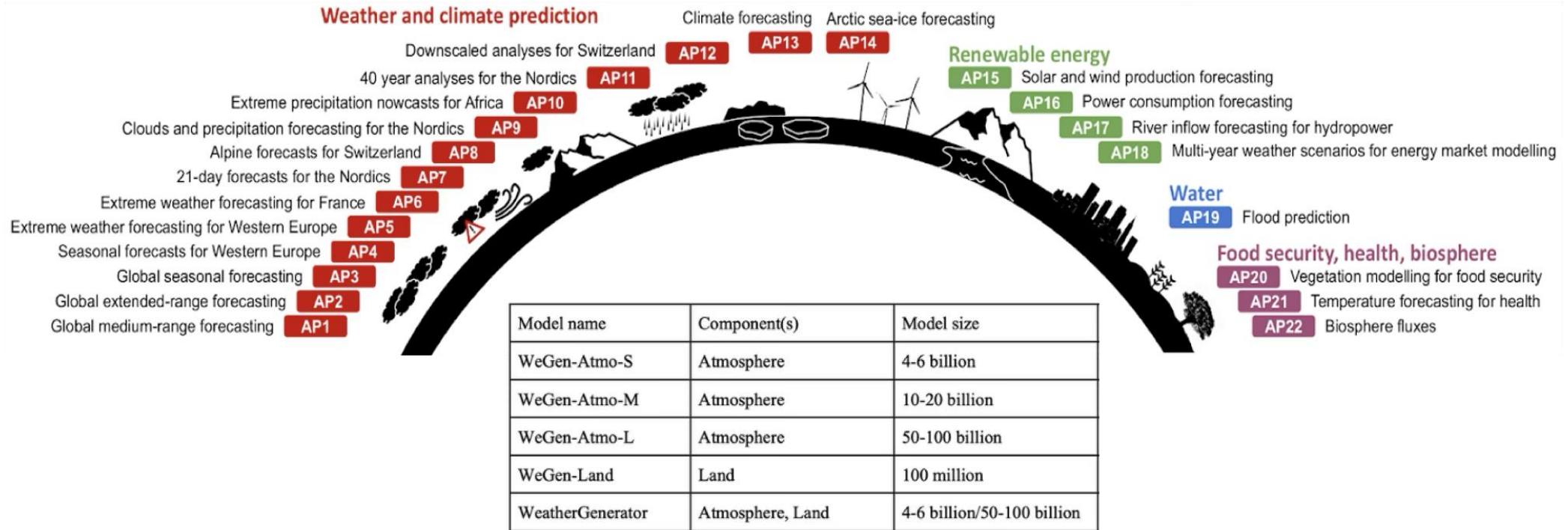
METEOSAT
Seviri, ch8



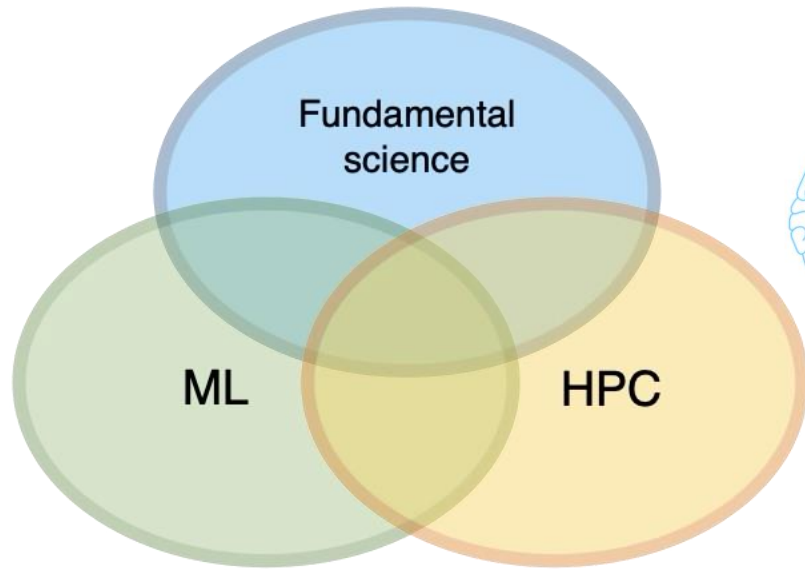
SYNOPSIS, T2m

<https://github.com/ecmwf/WeatherGenerator>

Downstream applications



Challenges



Scaling:

- **Efficiently scaling distributed training**
- **How to move to a stochastic model?**



Accessibility:

- **Deployment of the model for the different partners & the public**
- Knowledge distillation studies



Maintenance:

- **How to integrate new incoming data**
- How to **expand** to new fields/variables without fully retraining the model each time?

Some thoughts



Nobody knows where ML models will stand in 5 years from now

- How many models do we need?
- How will we integrate them with current NWP's?

There is no guarantee that this approach will work better than having multiple models

but

We need to stretch the boundaries of what we think it's possible with ML to shape the next generation of Earth system models



Funded by
the European Union

Coordinated by
ECMWF

RAINA



**Weather
Generator**

The RAINA project is funded by the Bundesministerium für Bildung und Forschung (BMBF) under grant agreement 01 IS24075.

THANK YOU

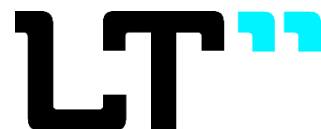
www.weathergenerator.eu



MAX PLANCK INSTITUTE
FOR BIOGEOCHEMISTRY



Royal Netherlands
Meteorological Institute
Ministry of Infrastructure
and Water Management



The WeatherGenerator project (grant agreement No101187947) is funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Commission. Neither the European Union nor the granting authority can be held responsible for them.