SCEWERO

Heatwaves: science, tools, and long-term trends

Lorenzo Sangelantoni

UNIVERSITATEA BABEȘ-BOLYAI
cmcc Centro Euro-Mediterraneo sui Cambiamenti Climatici
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN
Universiteit Antwerpen
indeco soft

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Talk outline

❑ Introduction to climate modelling

- The climate system;
- Global Climate Models (GCMs) vs Regional Climate Models (RCMs);
- Timescales in climate modeling: from weather to projections;
- Uncertainty: Deterministic vs. Probabilistic.

❑ Introduction to heatwaves (HWs)

- HWs definition;
- HWs detection;
- HW driving mechanisms. Large-scale vs. local-scale forcing.

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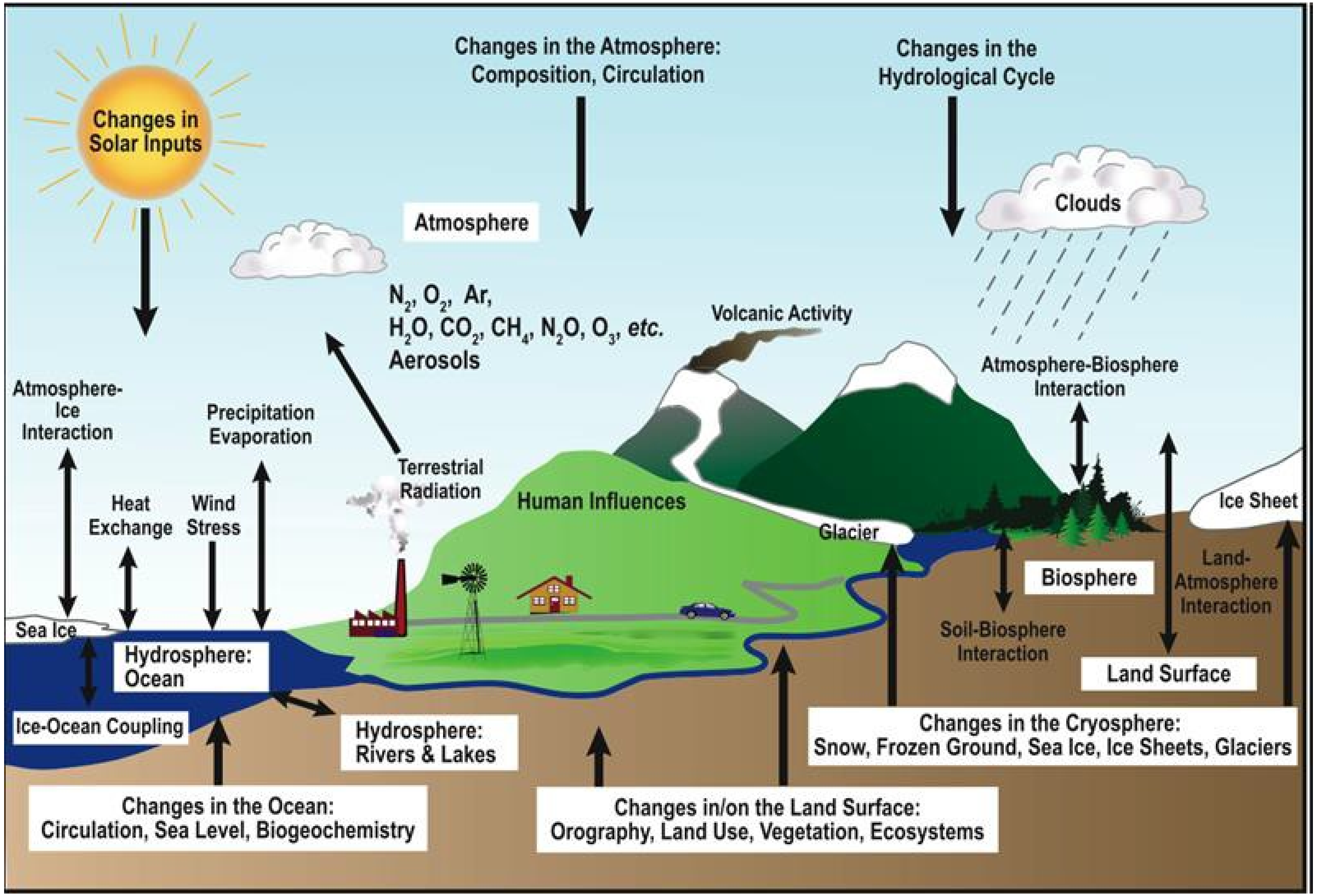
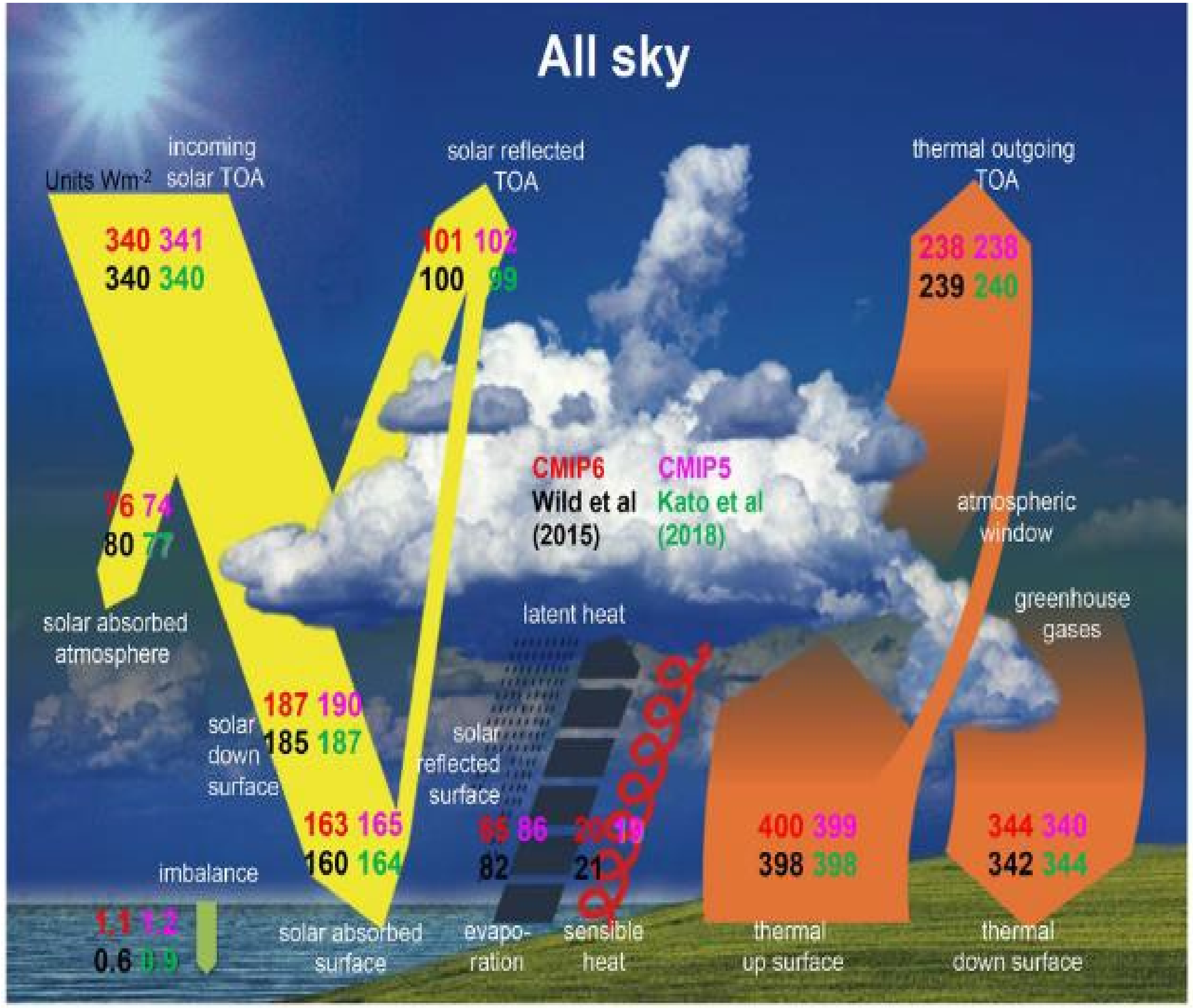
Modeling the climate system



IPCC AR4

The climate system



- The climate system is a forced, dissipative, nonlinear, complex and heterogeneous system that is out of thermodynamic equilibrium.
- The system exhibits **natural variability** on many scales, in time as well as space, and it is subject to **various external forcing**, **natural** as well as **anthropogenic.**

- Overall, the climate system can be seen as a thermal engine capable of transforming radiative heat into mechanical energy (atmospheric and oceanic circulations).

Ghil M, Lucarini V (2020) The Physics of Climate Variability and Climate Change. Rev Mod Phys 92

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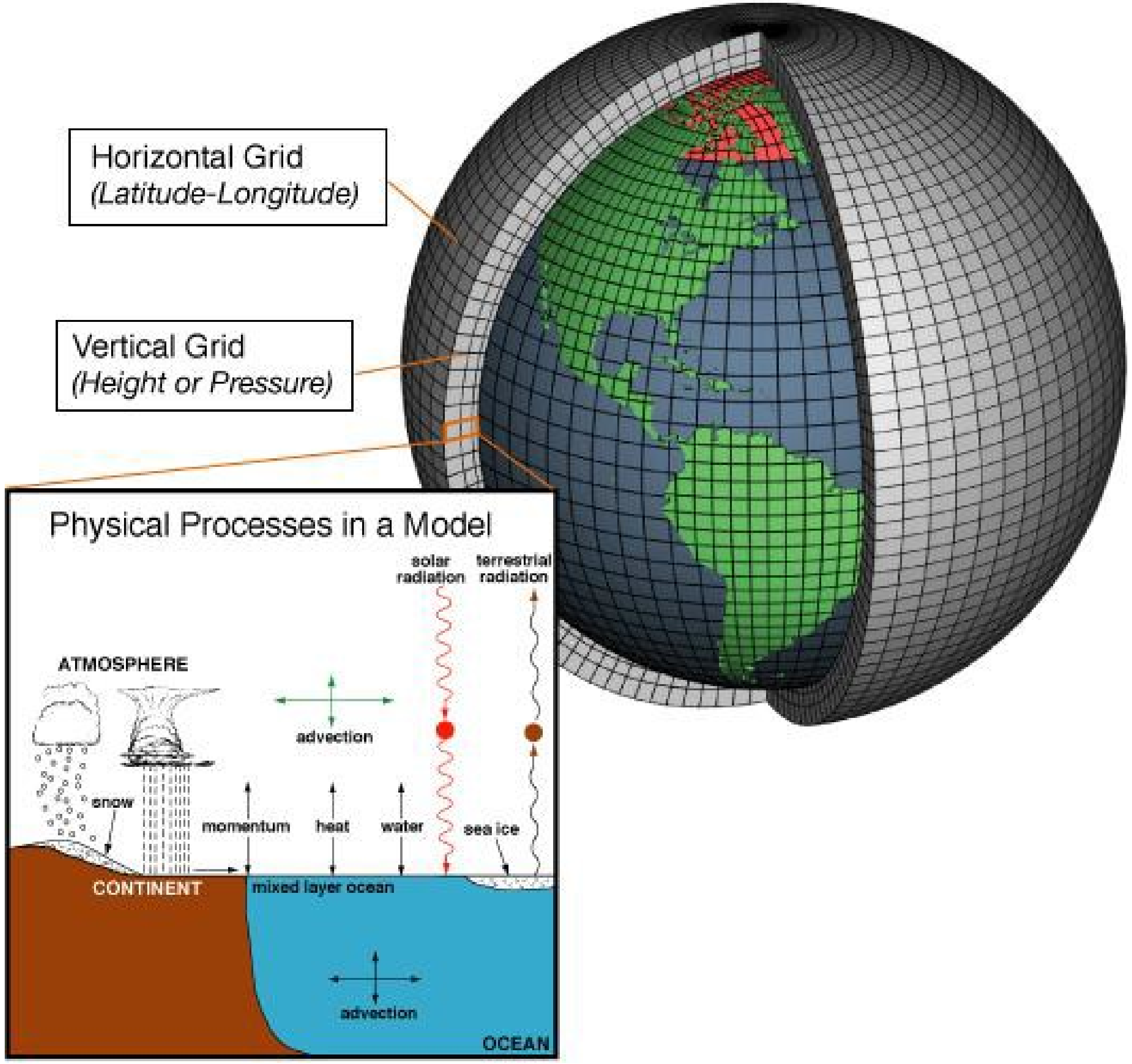
Modeling the climate system



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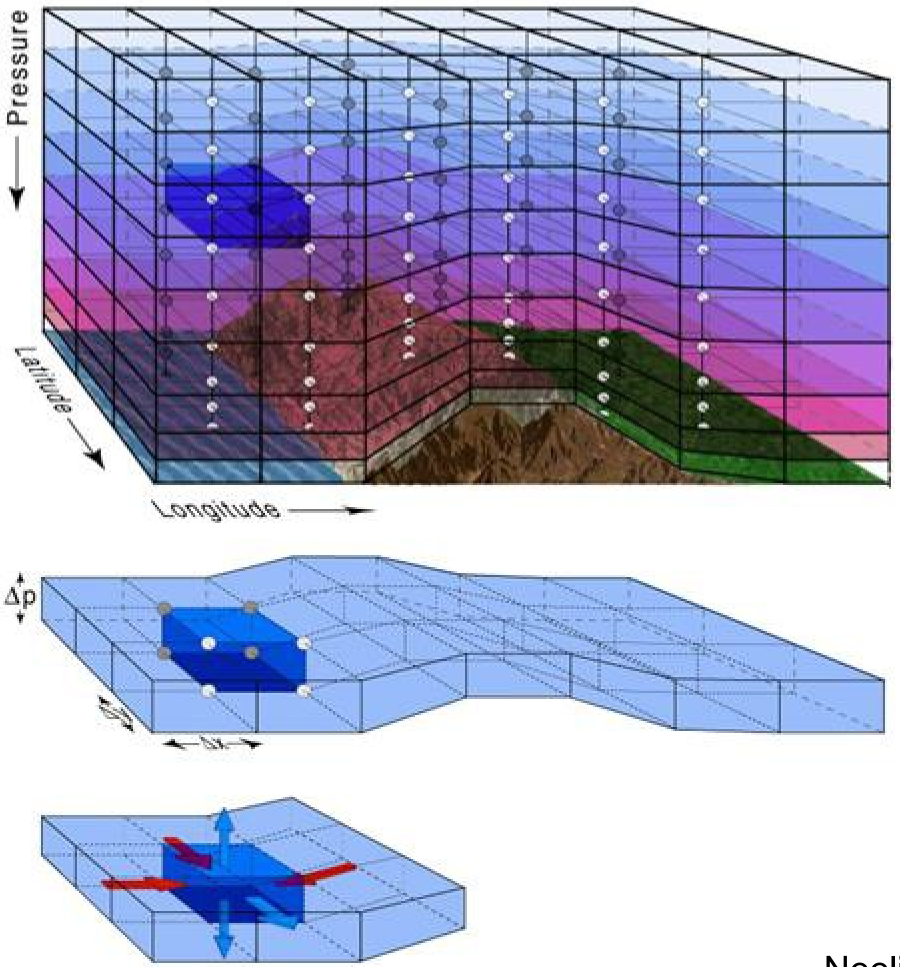
Modeling the climate system

Typical atmospheric GCM grid



- **For each grid cell, single value of each variable** (temp., wind, etc.).
- Vertical coordinate follows topography and is pressure coordinated. The horizontal grid is in latitude and longitude.
- **The partial differential eq. of the motion are replaced by a finite number of equations involving differences between values in neighboring grid cells**.
- **Each grid cell communicates with its neighbors in terms of transport** of mass, energy, and moisture.
- **The flux is proportional to differences between the grid cells for each variable**; the budgets of these fluxes are associated with the respective equation.

Neelin, 2011. *Climate Change and Climate Modeling,* Cambridge UP

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Modeling the climate system

Mathematical equations that represent the physical characteristics and processes are entered for each box

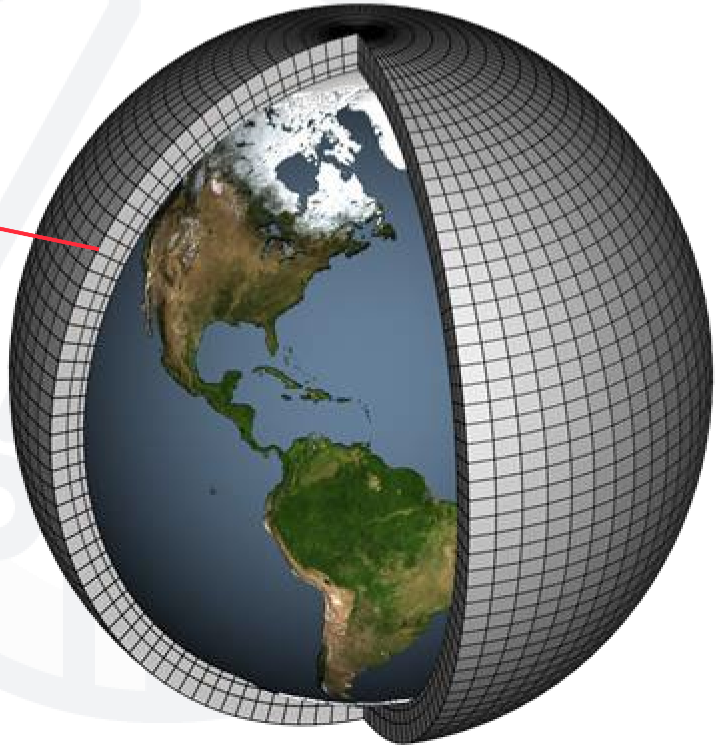
$$\frac{\partial u}{\partial t} = \eta v - \frac{\partial \Phi}{\partial x} - c_p\theta\frac{\partial \pi}{\partial x} - z\frac{\partial u}{\partial \sigma} - \frac{\partial(\frac{u^2+v^2}{2})}{\partial x}$$

$$\frac{\partial v}{\partial t} = -\eta\frac{u}{v} - \frac{\partial \Phi}{\partial y} - c_p\theta\frac{\partial \pi}{\partial y} - z\frac{\partial v}{\partial \sigma} - \frac{\partial(\frac{u^2+v^2}{2})}{\partial y}$$

$$\frac{\delta T}{\partial t} = \frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}$$

$$\frac{\delta W}{\partial t} = u\frac{\partial W}{\partial x} + v\frac{\partial W}{\partial y} + w\frac{\partial W}{\partial z}$$

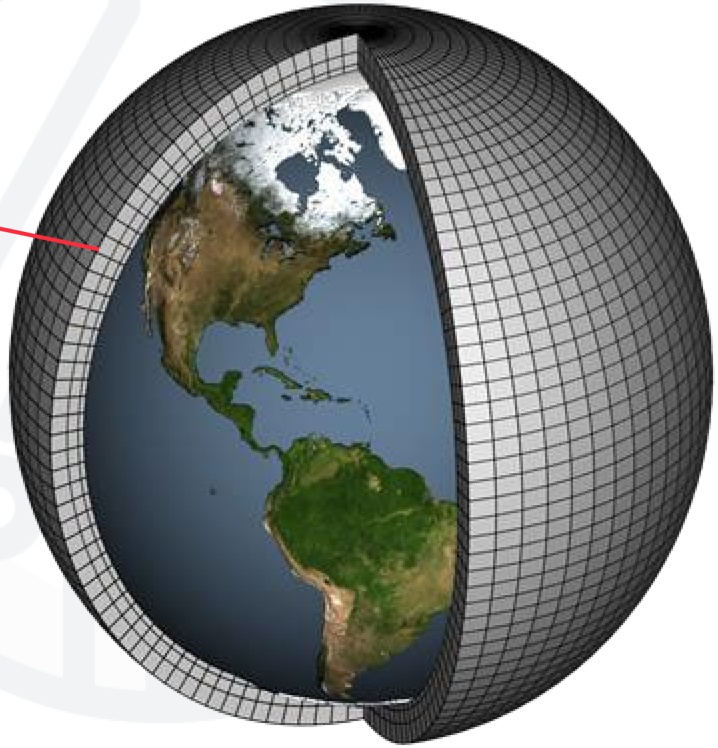
$$\frac{\partial}{\partial t}\frac{\partial p}{\partial \sigma} = u\frac{\partial}{\partial x}x\frac{\partial p}{\partial \sigma} + v\frac{\partial}{\partial y}y\frac{\partial p}{\partial \sigma} + w\frac{\partial}{\partial z}z\frac{\partial p}{\partial \sigma}$$



Modeling the climate system

Equations are converted to computer code and climate variables are set

```
if (diagts .and. eots) then
  do 1500 m=1,nt
    do 1490 k=1,km
      fx = cst(j)*dyt(j)*dzt(k)/(c2dtts*dtxcel(k))
      do 1480 i=2,imtm1
        boxfx           = fx*dxt(i)*fm(i,k,jc)
        sddt            = (ta(i,k,m)-t(i,k,jc,nm,m))*boxfx
        svar            = (ta(i,k,m)**2-t(i,k,jc,nm,m)**2)
                          *boxfx
        n               = 0
        termbt(k,1,m,n) = termbt(k,1,m,n) + sddt
        tvar(k,m,n)     = tvar(k,m,n)     + svar
        n      = nhreg*(mskvr(k)-1) + mskhr(i,j)
        if (n .gt. 0 .and. mskhr(i,j) .gt. 0) then
          termbt(k,1,m,n) = termbt(k,1,m,n) + sddt
          tvar(k,m,n)     = tvar(k,m,n)     + svar
```



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Modeling the climate system

CASSANDRA

Compute node type: LENOVO SD650 V3 (Direct Water Cooled)

Processor type: Intel Xeon Max 9480 (56 cores) (Sapphire Rapids HBM)

Processor Speed: 1.9 GHz

# of processor cores: 20,160

 # GPU: n.a.

# of nodes: 180 (dual processors nodes)

Memory per node: 1024 GB

Interconnection: Infiniband NDR (400Gbps)

Peak Performance: 1,225 TFlops

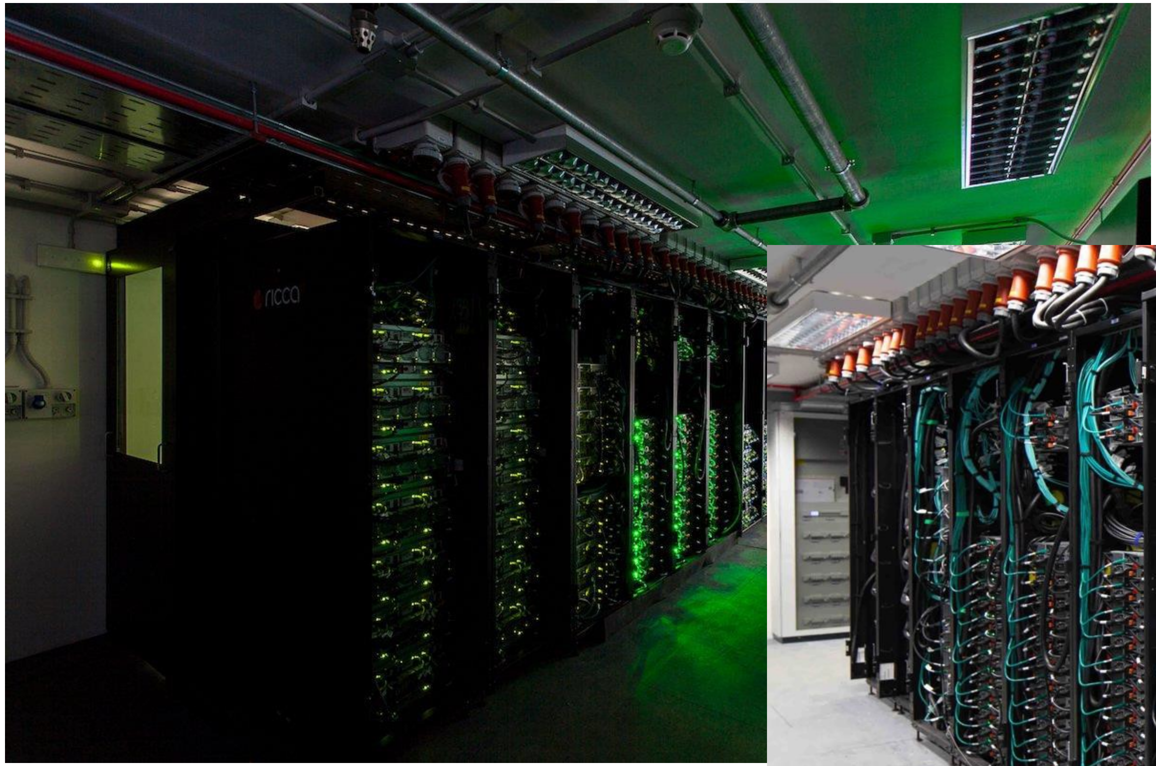
Operating System: Red Hat v.9.0 (Linux x86_64)

Batch Queueing System: IBM Spectrum LSF v.10.x (HPC Suite)

Cluster Parallel File System: IBM Spectrum Scale v.5.x (GPFS)

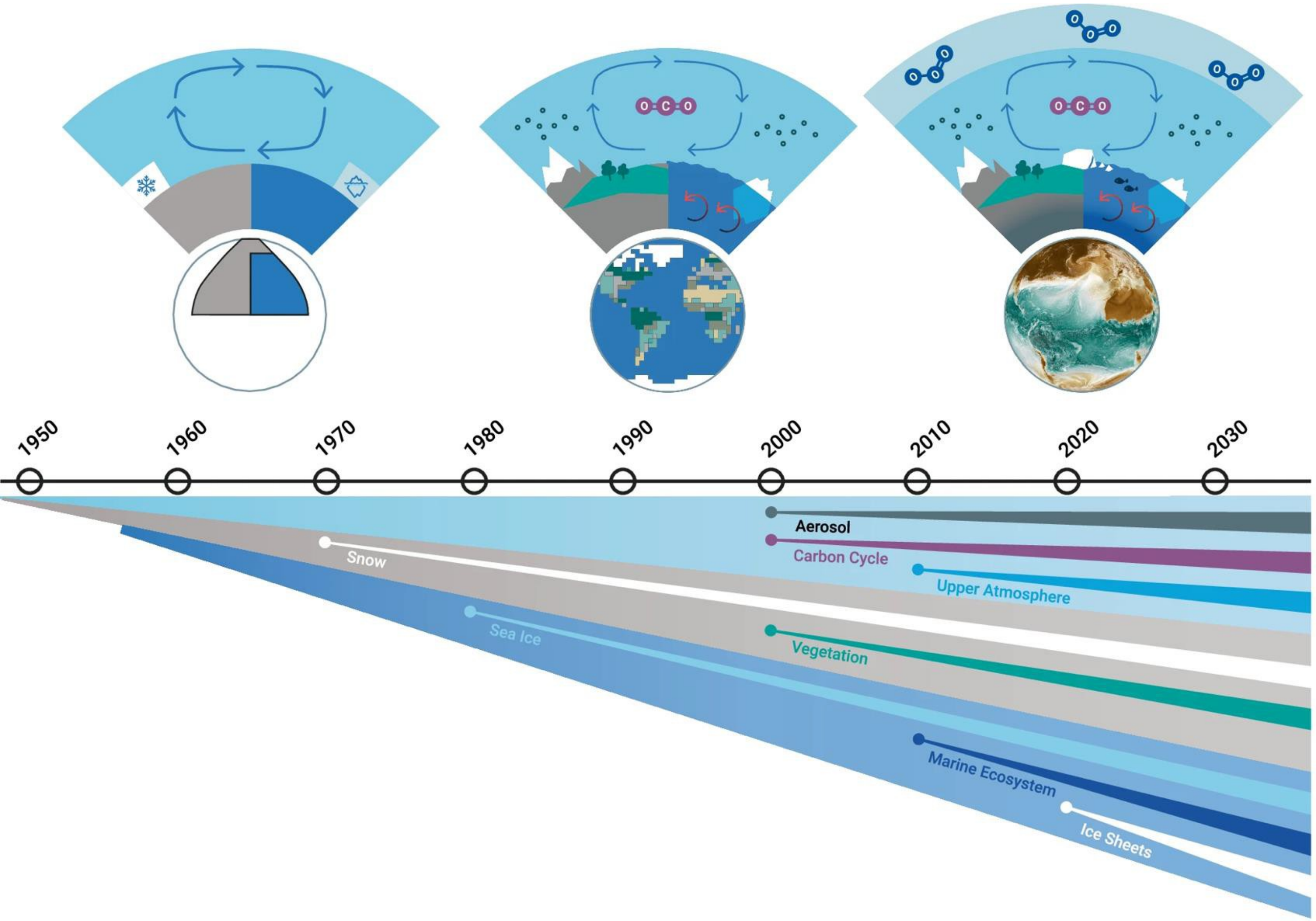
File systems:

- /users_home: 100TB
- /work: 13.6 PB of usable capacity



Super Computer helps on these computations

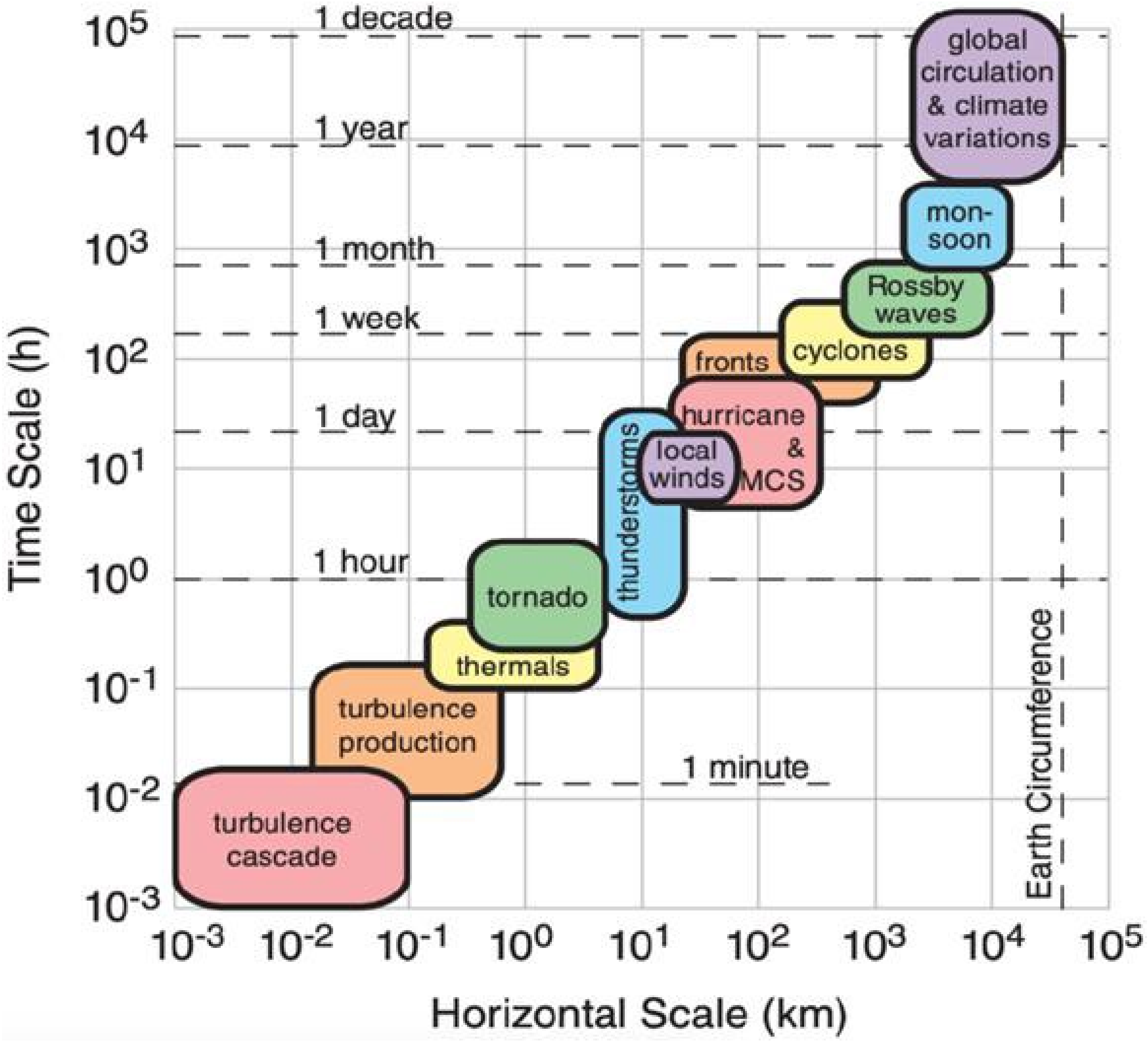
Modeling the climate system



The list of **components** and **processes** reproduced in the numerical models increased in time thanks to the **technological (and knowledge) improvements.**

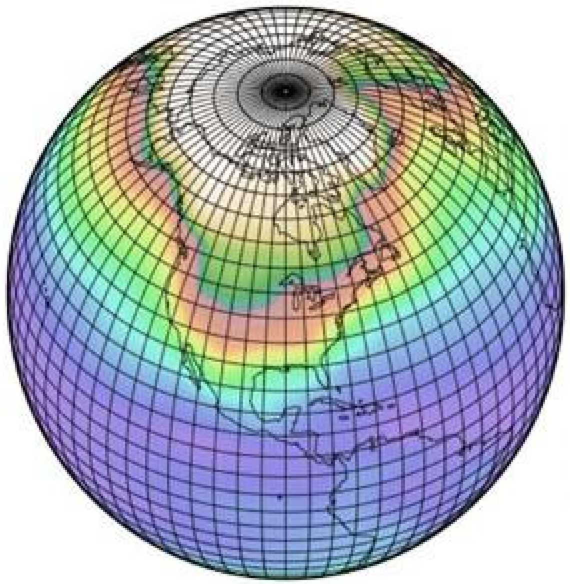
Progression of model components from early climate models to the latest Earth System Models. From Bordoni et al., 2025

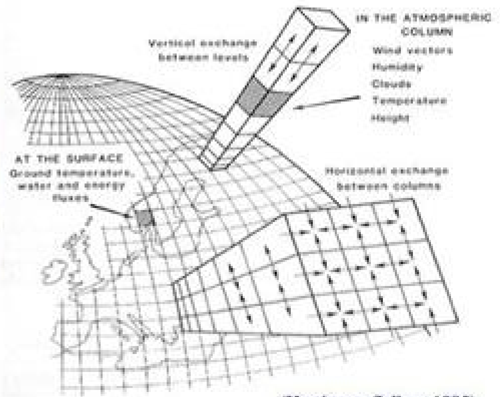
Timescales in climate modelling



Stergiou 2023

Global Climate Models (GCMs)





(Henderson-Sellers, 1985)

- **<u>GCMs</u>** comprise **atmosphere**, **ocean** and **sea ice** components
- They are coupled so **they can exchange energy, momentum and moisture**. Recent versions also contain model components for **dynamic vegetation and the terrestrial and ocean carbon cycle**. These more comprehensive models are known as **<u>Earth System Models (ESMs).</u>**
- The simulated states are given on three-dimensional spatial grids and at discrete time steps, and the model equations describe how the system evolves in time.
- The horizontal grid resolution for the atmosphere component of GCMs in climate applications is usually on the order of 200-25km, the number of vertical levels between 30 and 100, starting at the surface and including the troposphere and to varying extents the stratosphere.

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Global Climate Models (GCMs): Parametrizations

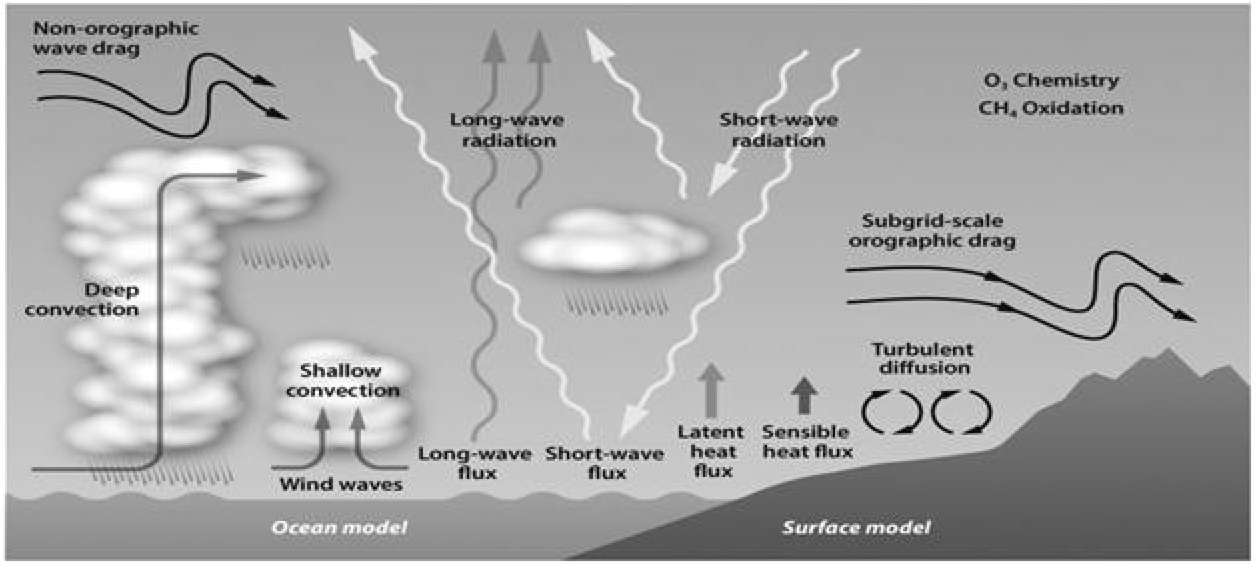
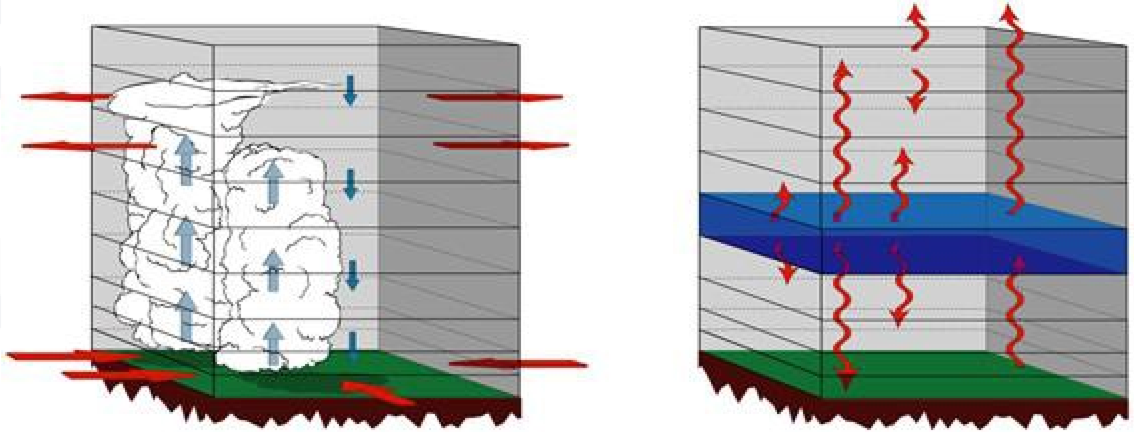


Figure 8.4 Parameterised processes in atmospheric general circulation models. Figure provided by ECMWF https://www.ecmwf.int/en/research/modelling-and-prediction/atmospheric-physics. Copyright given through Creative Commons license version 4.0 (https://creativecommons.org/licenses/by-nc-nd/4.0/legalcode).

Cambridge University Press 978-1-107-06605-2 — Statistical Downscaling and Bias Correction for Climate Research D. Maraun , M. Widmann 2019

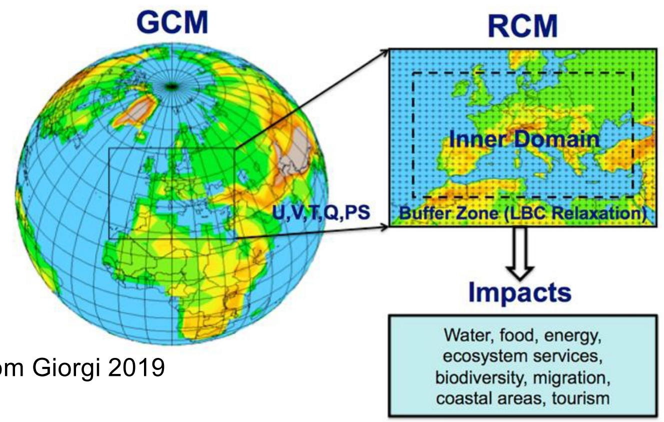
There are many process in the real atmosphere and ocean that occur on spatial and temporal scales smaller than the model resolution. In the atmosphere these include radiation absorbed, scattered and emitted by molecules, aerosols and cloud droplets, cloud microphysics, convection, boundary layer processes, drag caused by orography atmosphere-ocean interaction, etc.



Neelin, 2011. *Climate Change and Climate Modeling,* Cambridge UP

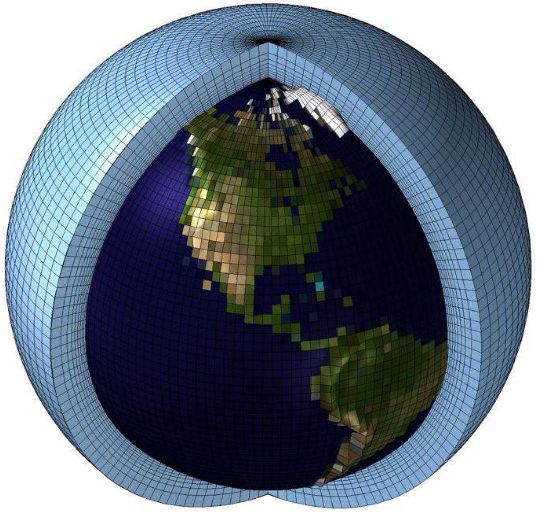
Regional Climate Models (RCMs)

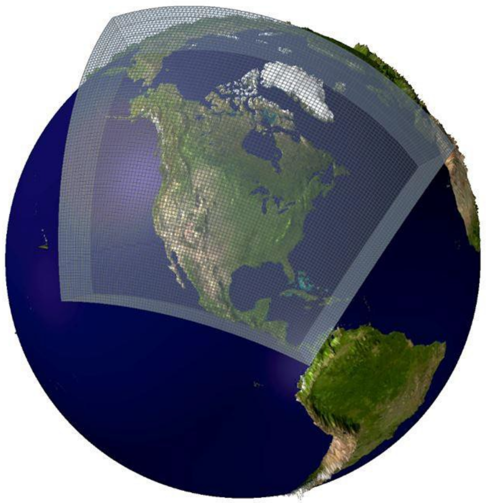
RCMs are idealized to resolve the scale discrepancy between climate change scenarios required for impact assessment or for resolving highly localized phenomena.



From Giorgi 2019

- RCMs are used for dynamical downscaling over a **limited domain**.
- **They are forced at the lateral domain boundaries** and typically sea surface by values from GCMs.
- The nesting of the RCM into the driving GCM is typically **one way.**
- To reduce the gap in resolution between the driving and nested models, also several **subsequent nests** can be applied.
- **To avoid numerical instabilities a sponge zone** of typically 10 grid boxes at the boundary of the RCM domain is created. **Here, the GCM boundary conditions are gradually blended into the RCM**.





From https://www.ouranos.ca/en/science-du-climat-modelisation-climatique

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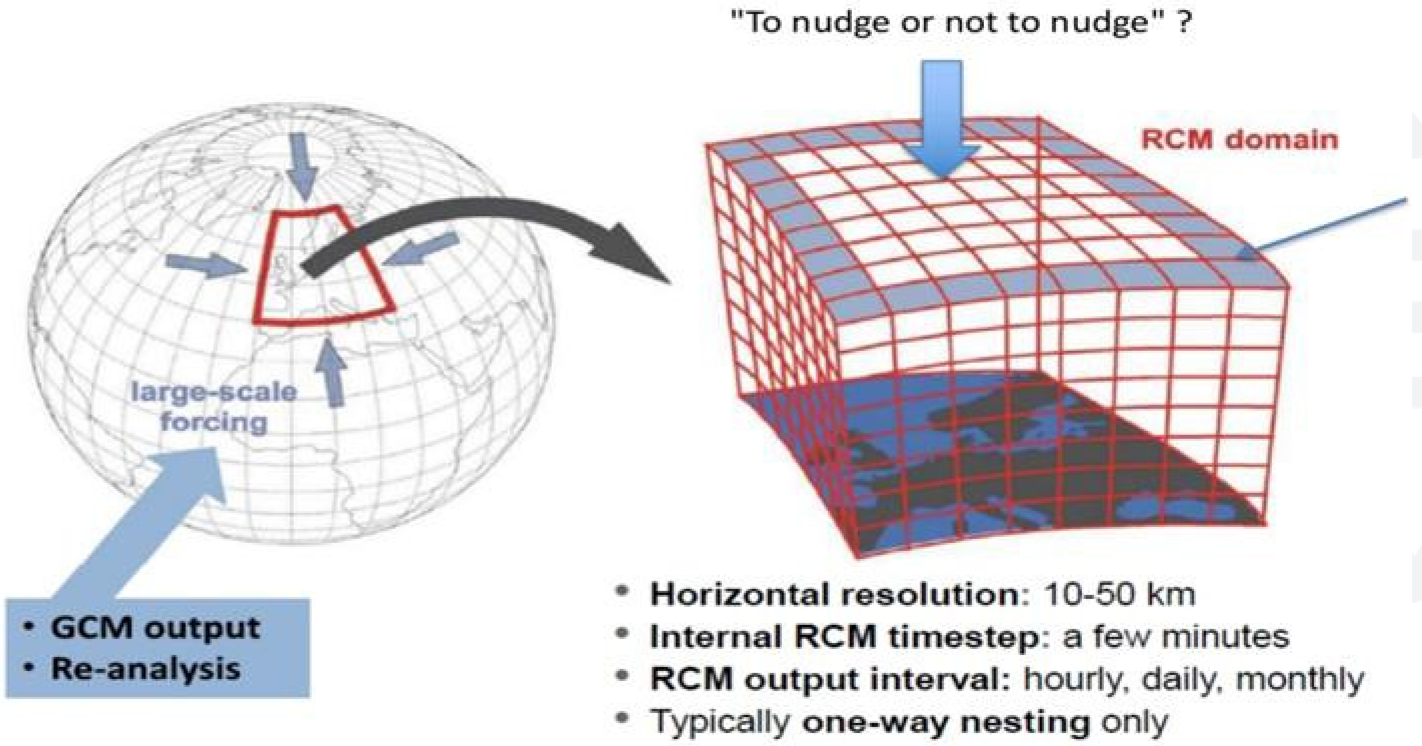
Dynamical downscaling



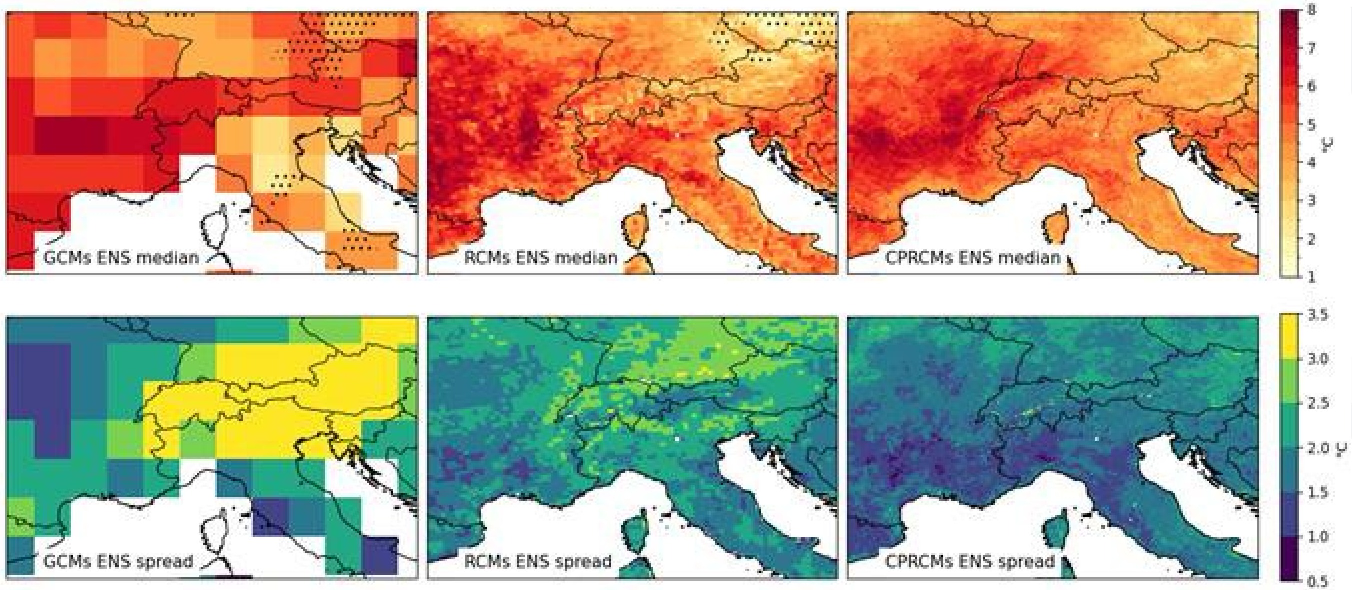
From J. H. Christensen 2018

- Uses a **Regional Climate Model (RCM)**
- **Physically-based**: solves atmospheric equations
- Computationally expensive
- Captures **local feedbacks**, extremes, terrain effects
- Example: CORDEX simulations

Regional Climate Models (RCMs)

- **At the boundaries, the RCM is (more or less) consistent with the driving GCM. <u>Within the domain, the RCM simulates weather consistent with its own topography, dynamical core, resolution and parameterisations and develops its own internal variability.</u>**
- This implies that the large-scale atmospheric states within the model domain can be different from the GCM states over the domain. **Depending on the context, this "independence" may be desirable or undesirable.**

Mean HW days tmax change signal 2090:2099 – 1996-2005



From Sangelantoni et al., 2025

Future heatwave temperature changes from 100km to 3 km resolution.

Uncertainty associated to the future changes at the different resolutions.

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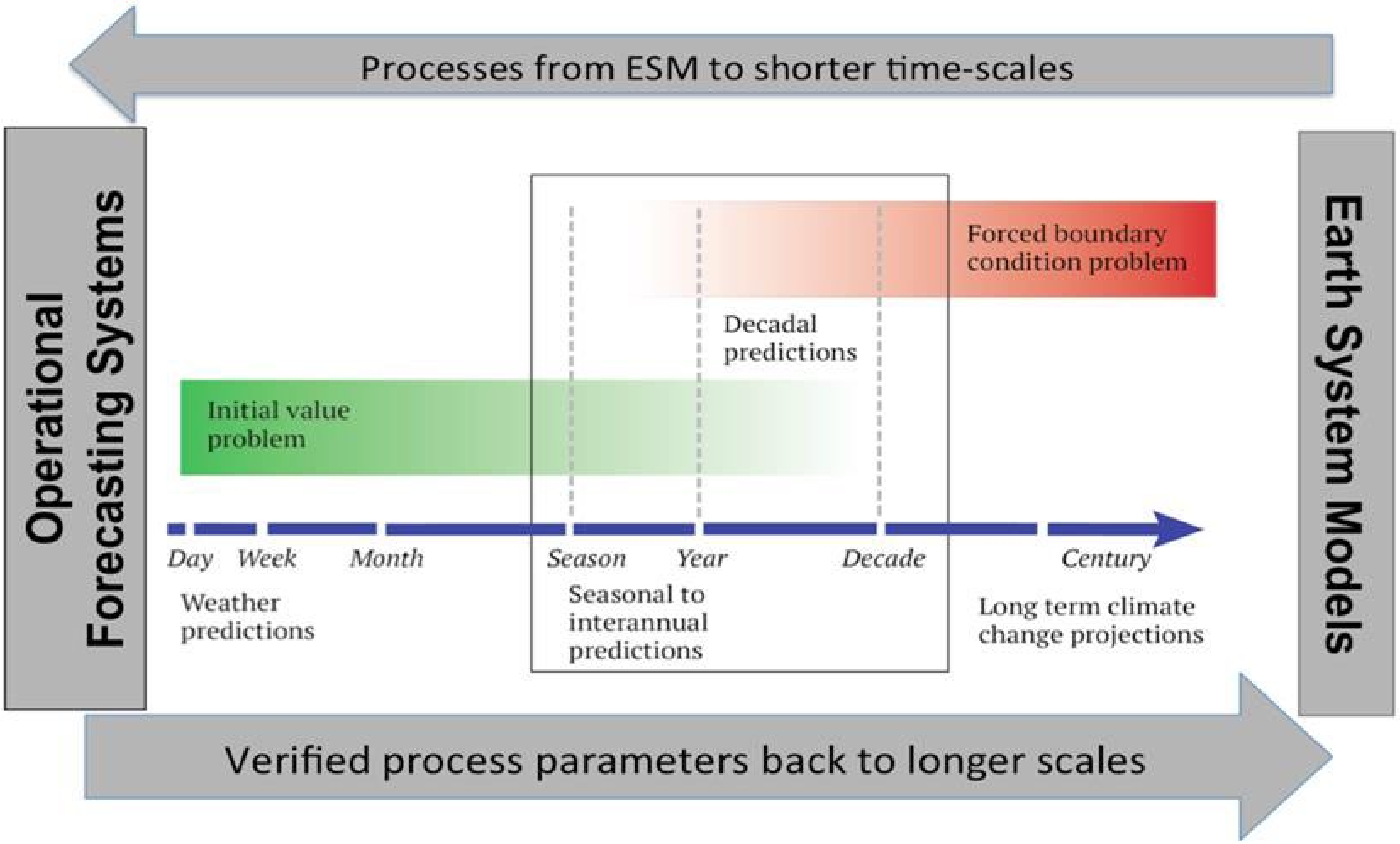
Timescales of climate information



A. Alessandri, F. Catalano, M. De Felice, B. Van Den Hurk, F. Doblas Reyes, S. Boussetta, G. Balsamo, and P. Miller, 2017: Multi-scale enhancement of climate prediction over land by increasing the model sensitivity to vegetation variability in EC -Earth, Clim. Dyn, 49(4), 1215-1237. doi:10.1007/s00382-016-3372-4

https://www.isac.cnr.it/en/temi-di-ricerca/Climate-modelling

Uncertainty: Probabilistic vs Deterministic

- Many sources of uncertainty exist.

•Ensembles capture this uncertainty by running multiple simulations.

- Ensemble generation methods consist of perturbing:
  - initial conditions,
  - model physics,
  - external forcings,
  - considering several models.

Soret et al., 2025

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Heatwaves

HW definition(s)

- In the scientific literature a plethora of HW definitions can be found.

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HW definition(s)

- In the scientific literature a plethora of HW definitions can be found.
- “a period of **abnormally hot weather**, often defined with reference to a relative temperature threshold, **lasting from 2 days to months**.” (IPCC: Annex VII: Glossary, 2021).

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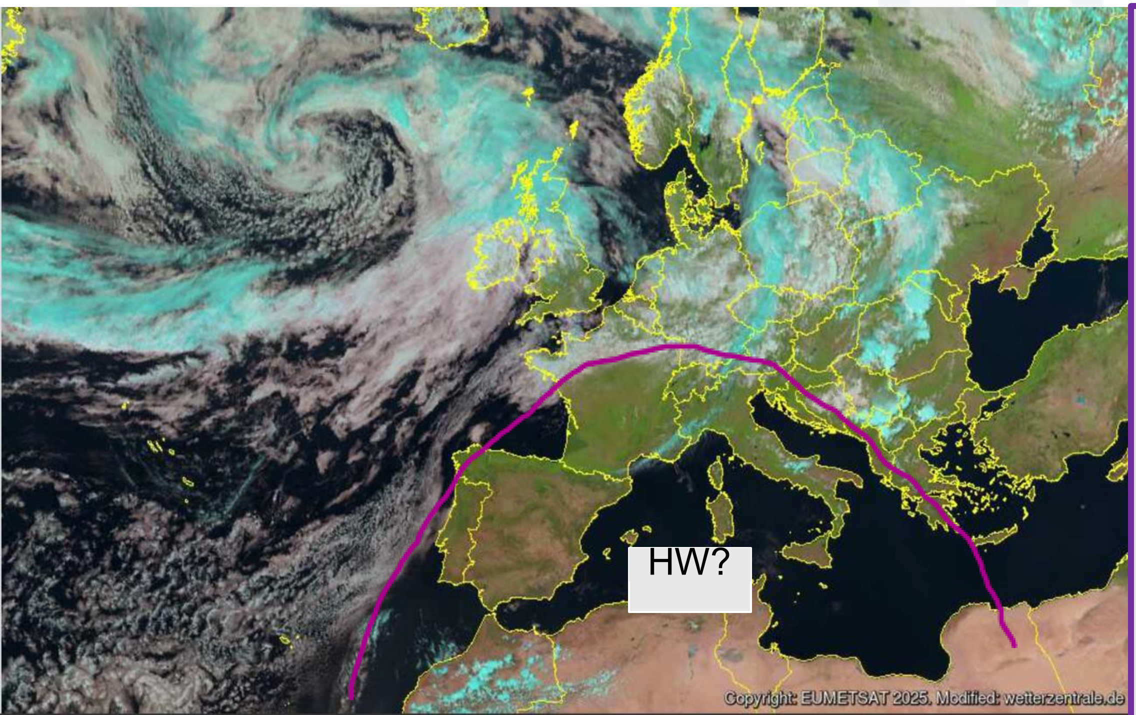


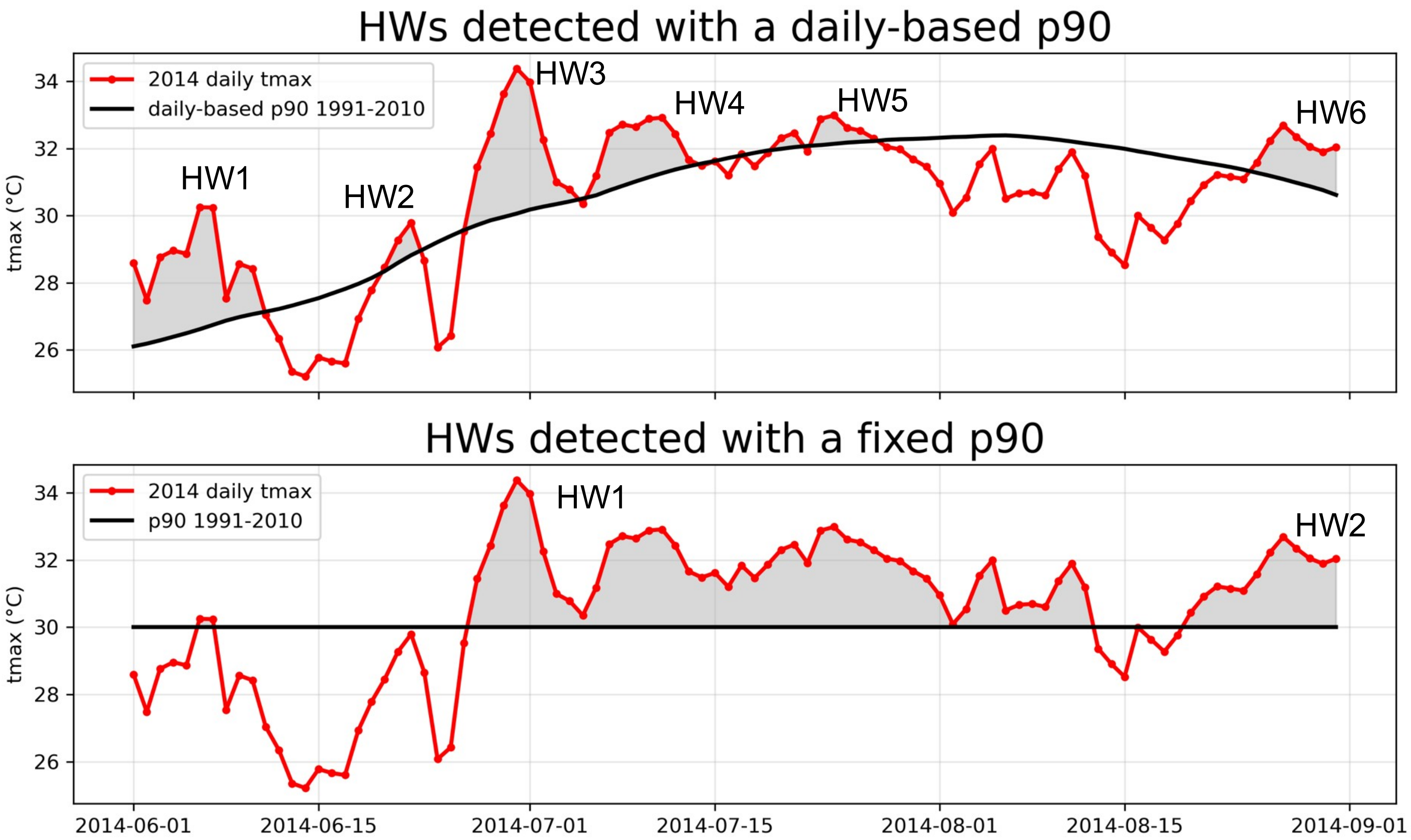
What prevents us from agreeing on what a HW actually is?

“Degrees of Freedom” of HW definition

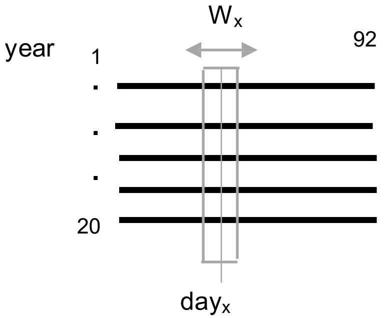
- **Variables.** tmean | tmin | tmax?
- **Statistics.** p90 | p95 | p99? PDF built on the whole year or JJA days?
- **Reference period** (e.g., 1961-1990 | 1991-2020)?
- **Persistence.** 2 | 3 | 5 | 7 consecutive days?

This clearly makes very dependent on the case study…

HWs detection, in practice



- Daily-based p90 (31-day time window).



- Fixed p90 tmax.

Heatwave physical drivers

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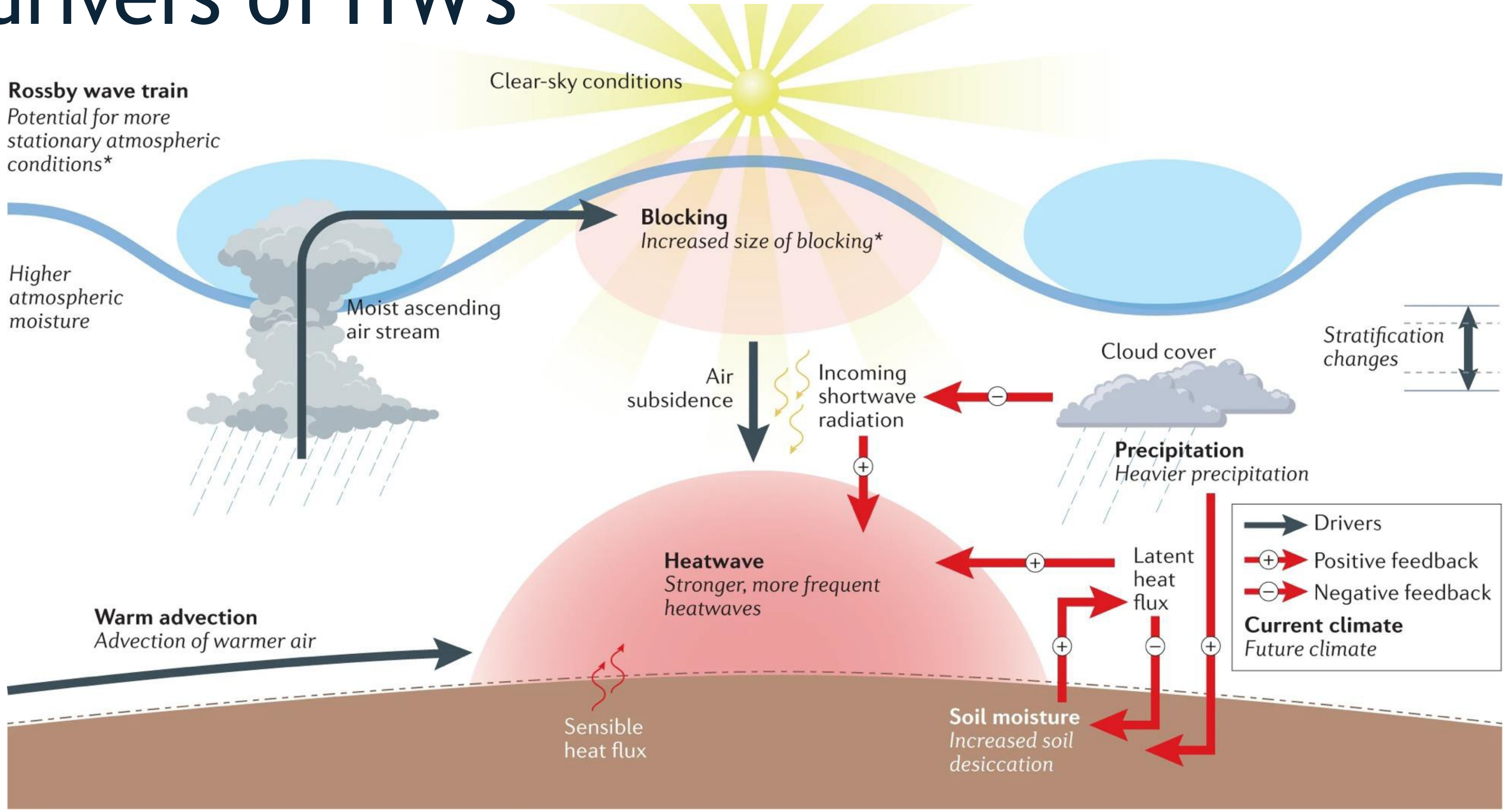
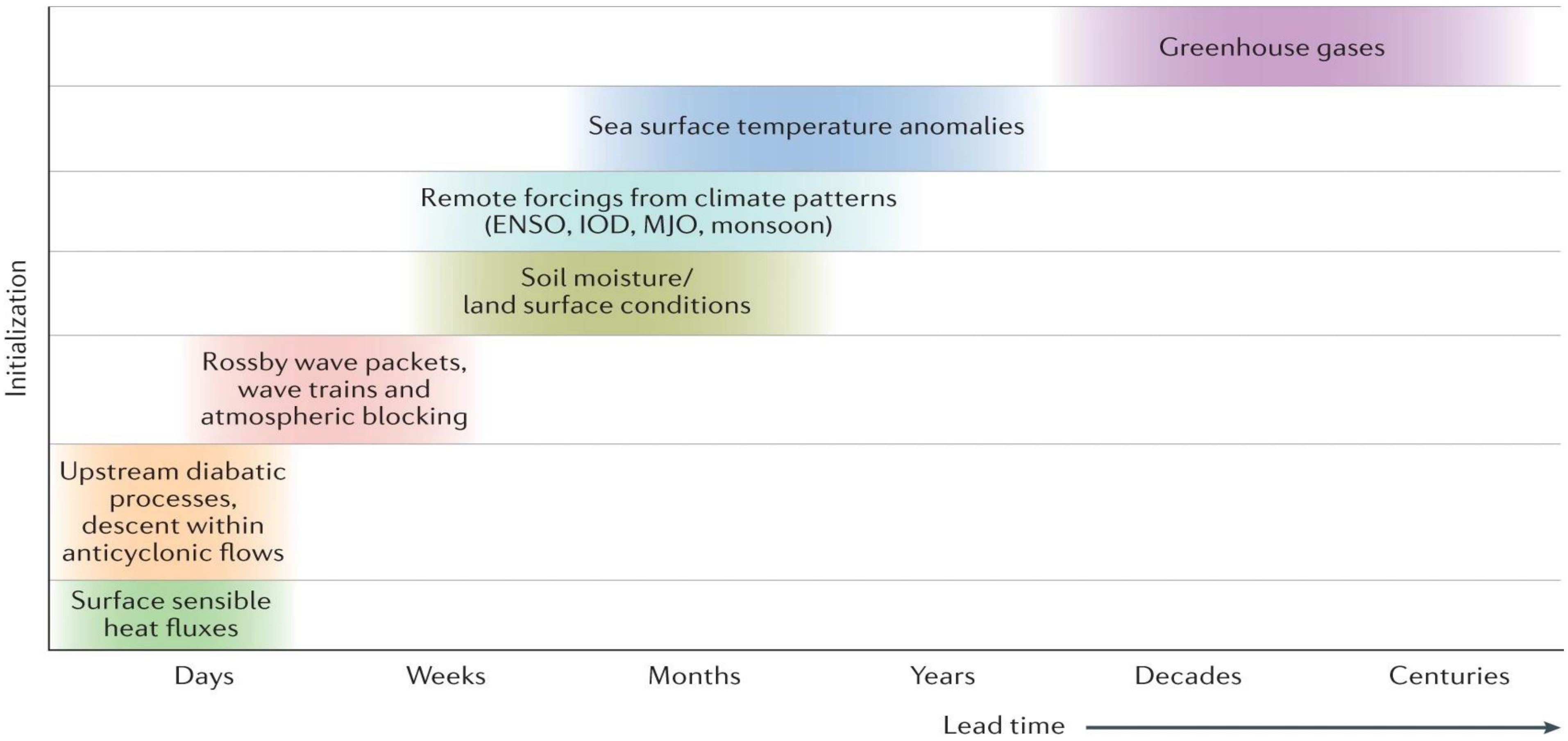
Physical drivers of HWs



Domeisen et al., 2023

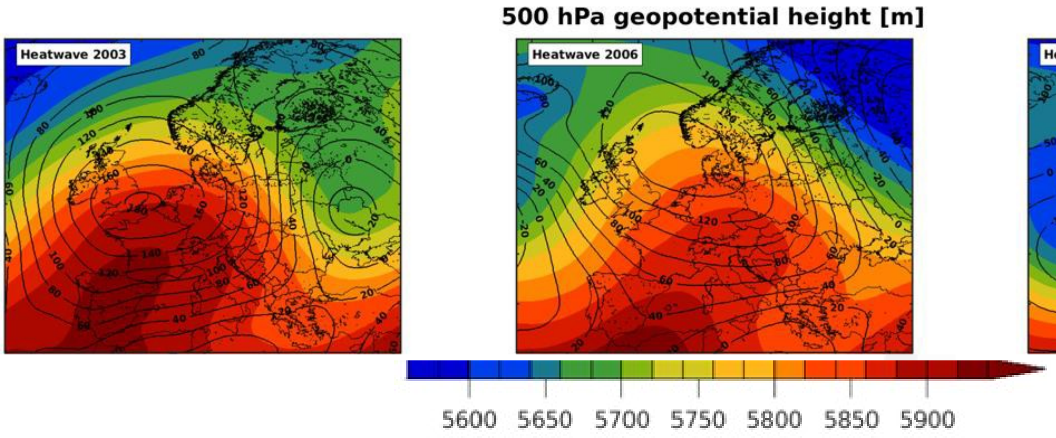
- The fist HW ingredient is the onset of particular large-scale configurations dominated by Rossby waves determining high-amplitude upper tropospheric ridges.
- Upper-level ridge and blocking promotes surface HWs via (i) clear skies and high radiation, (ii) subsidence, the compression and subsequent warming of upper levels air masses, (iii) advection of southernly climatologically warmer air masses, and (iv) it comes to play thermodynamics with diabatic heating due to the progressive increase of sensible heat flux due to the progressive desiccation of soil and the subsequent reduction of latent heat.

Physical drivers of HWs



Domeisen et al., 2023

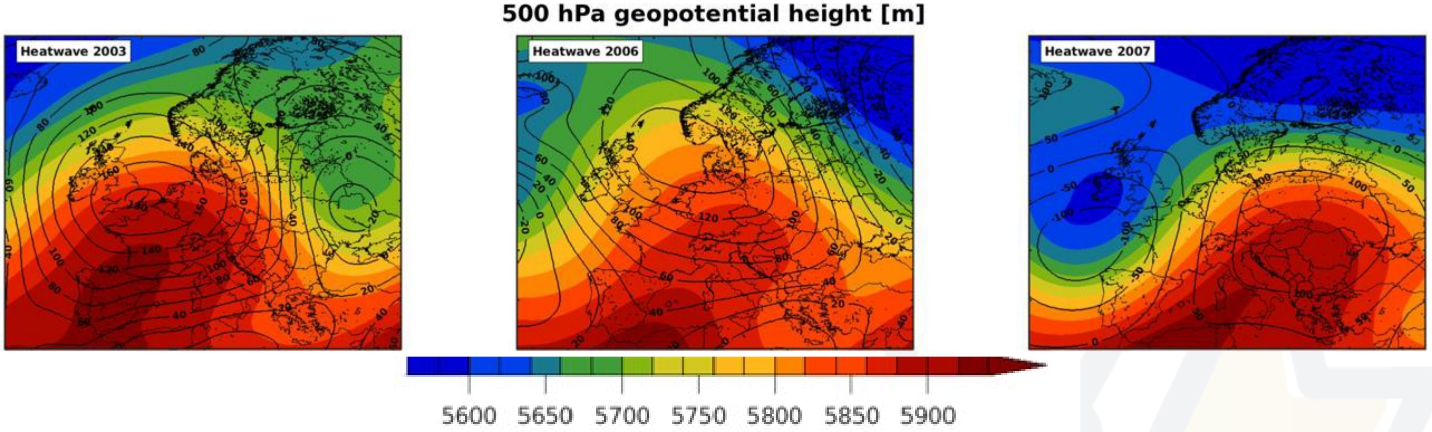
Physical drivers of HWs. Large-scale forcing



From Sangelantoni et al., 2023

- An imperative driver of HWs is atmospheric circulation which in turn can modulate the degree of influence of other drivers.

Physical drivers of HWs. Large-scale forcing



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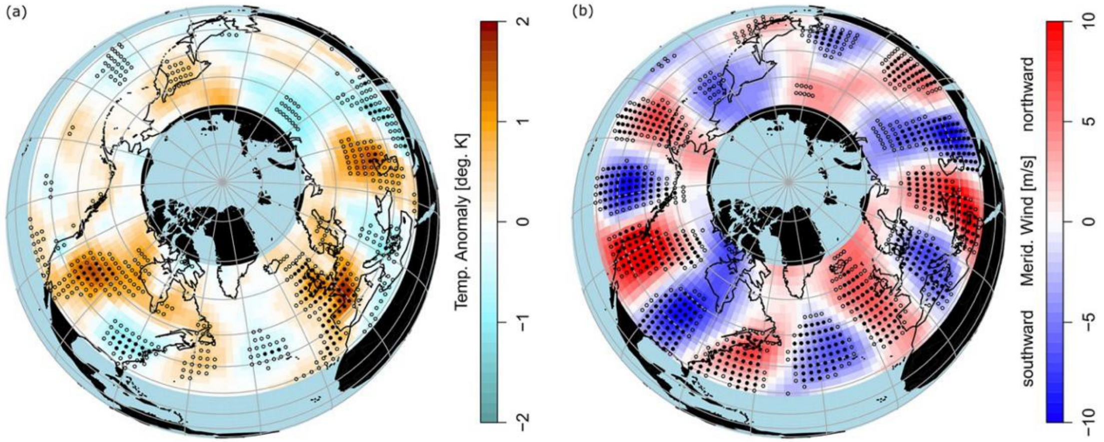


- In mid-latitude regions HWs generally emanate as a **regional manifestation** of **quasi-stationary Rossby waves pattern**.
- Hemispheric Rossby wave packets with a local maximum amplitude and limited zonal extent meridionally confined by the waveguides effect of the jet.

Composites of JJA weeks characterised wavenumber-7 events. Surface temperature anomaly (a) and corresponding 300 hPa meridional wind speed (1979–2018).

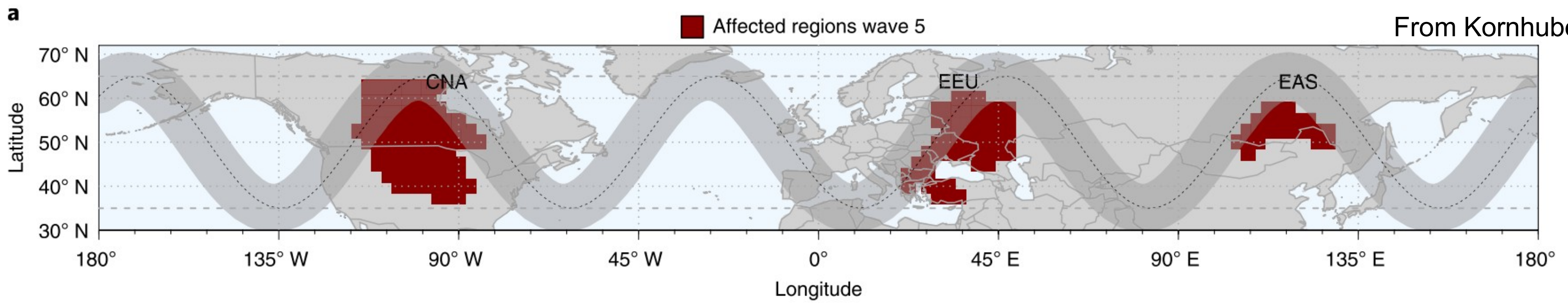
From Kornhuber et al., 2019

Physical drivers of HWs. Large-scale forcing

- Summer waveguides can circumvent the whole hemisphere establishing circumglobal teleconnections (CGT, Branstator 2002). CGTs can eventually persist synchronizing weather extremes through the hemisphere.

Coincidence of heatwaves in regions teleconnected by wave 5

From Kornhuber et al., 2020



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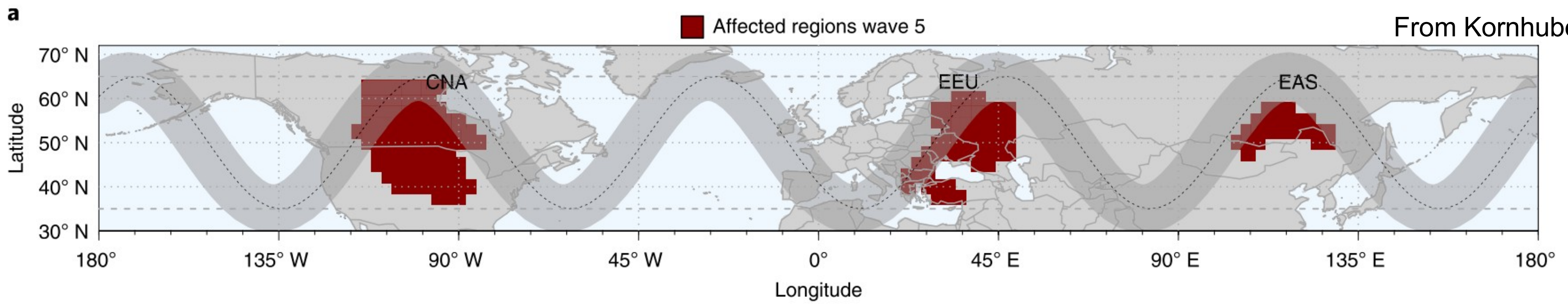

From Kornhuber et al., 2020

Why do CGTs end up in a phase locking amplification?

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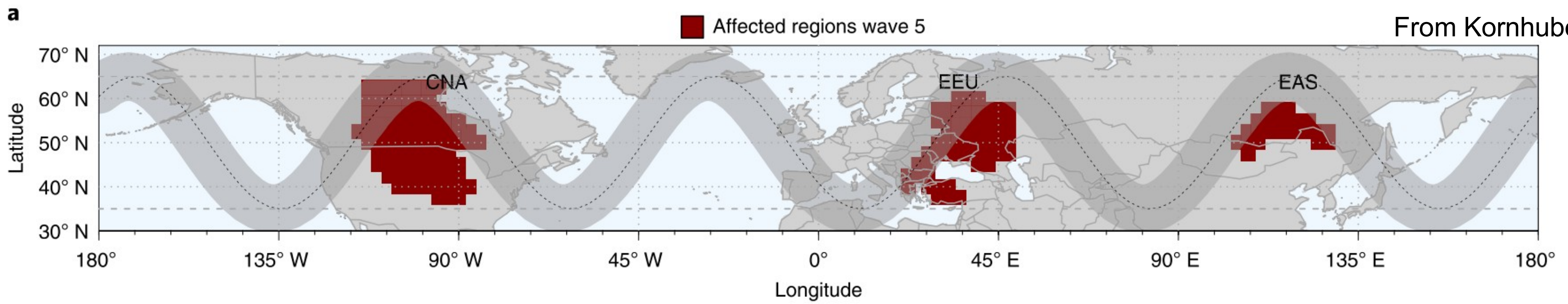


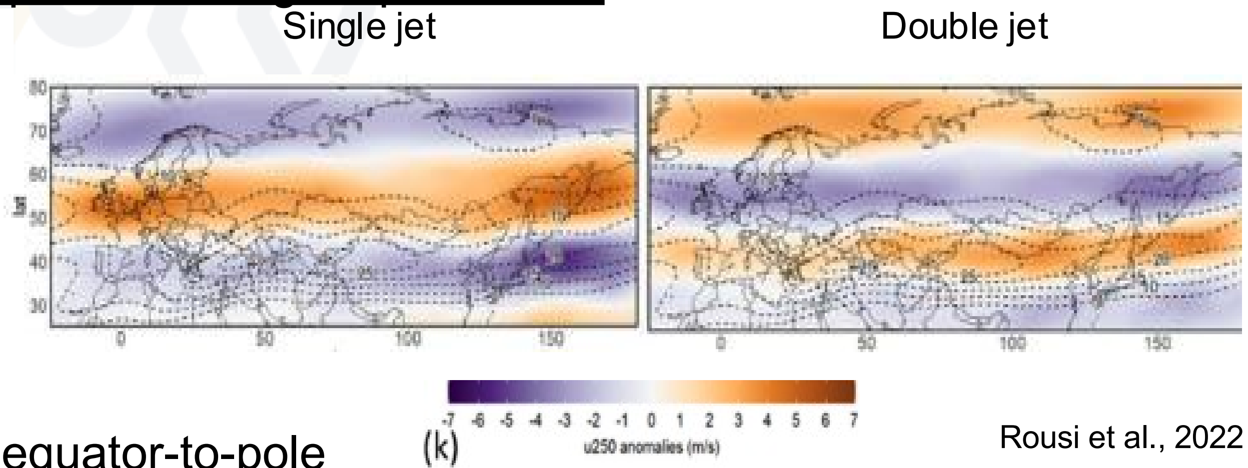
From Kornhuber et al., 2020

Why do CGTs end up in a phase locking amplification?

Two main mechanisms:

(i) Weakening of the zonal mean jets.

(ii) Double-jet configuration (trapping of free synoptic Rossby waves with k≈6−8 within the midlatitude waveguides).



Rousi et al., 2022

These dynamics seem to be ultimately driven by a reduced equator-to-pole thermal gradient due to Arctic amplification (Petoukhov et al., 2013 and Comou et al., 2014).

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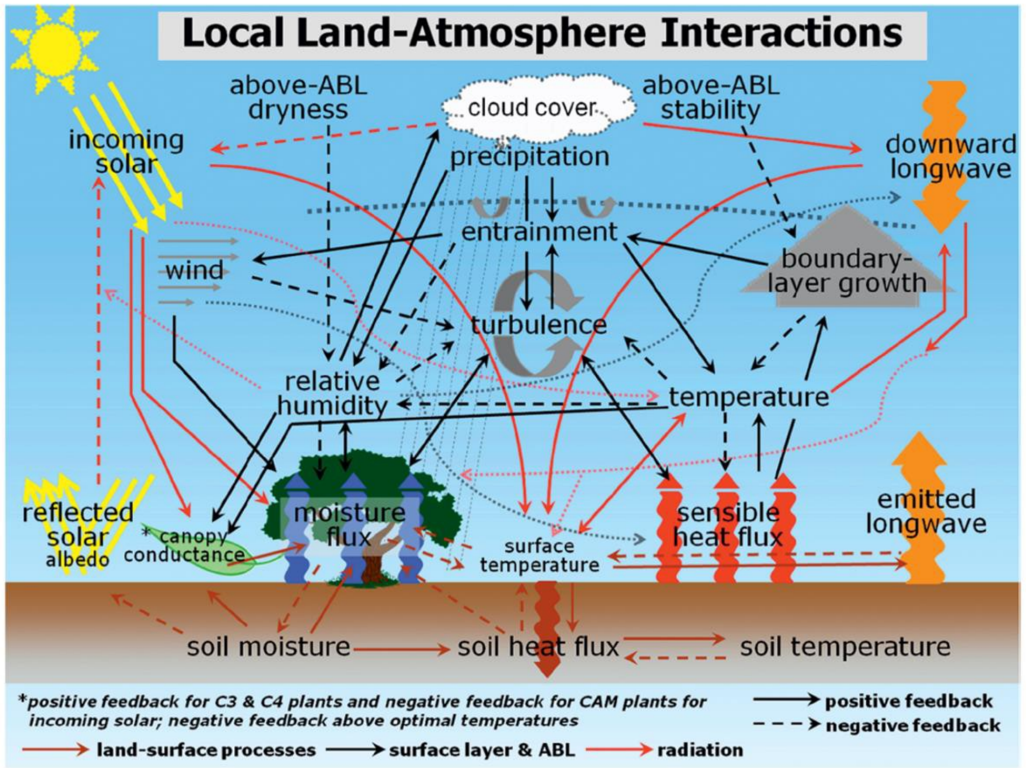
Regional-to-local-scale forcing

…Even though high-pressure systems are a necessary ingredient for the development of HWs, regional factors can substantially modulate the onset and evolution on a wide range of temporal scales…

Regional-to-local-scale forcing



Schematic land-atmosphere interactions in a quiescent synoptic regime.

Land-atmosphere interactions represent exchanges of energy, mass, and momentum at the Earth's surface. Land-atmosphere coupling **affects planetary boundary layer (PBL or ABL) evolution**, convection, and cloudiness, which in turn affect precipitation generation and the intensity and duration of heat waves.

PBL: part of the troposphere directly affected by surface conditions, ranging from several hundred meters to a few kilometers in depth. Distinguishable from the free troposphere above it by differences in flow, thermodynamic properties, and chemical content.

From Santanello et al., 2018

Regional-to-local-scale forcing

How land surface state affects the atmosphere

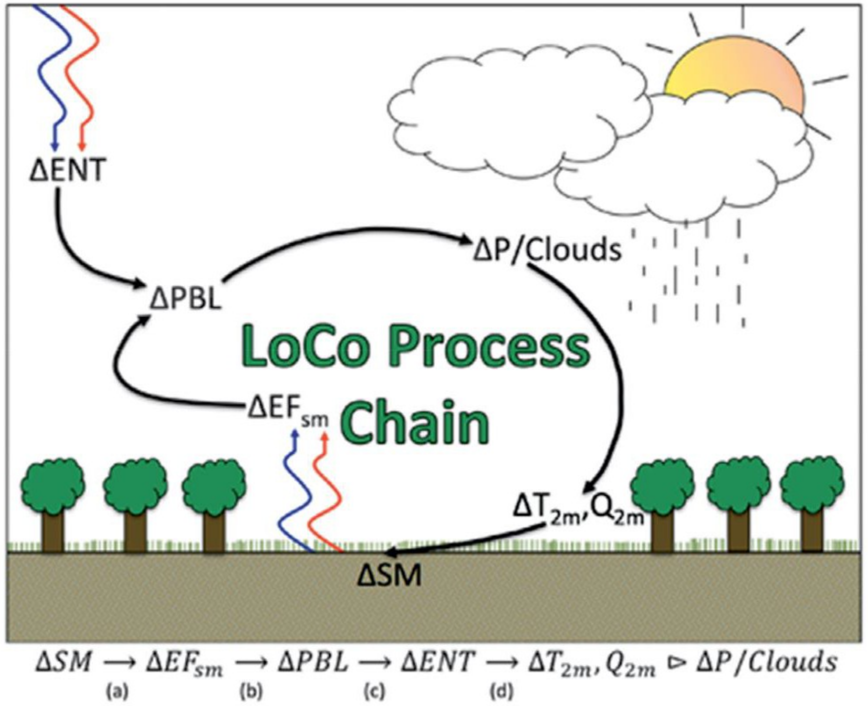


Fig. 2. Schematic of the LoCo process chain describing the components of L-A interactions linking soil moisture to precipitation and ambient weather (T_{2m}, Q_{2m}), where SM represents soil moisture; EF_{sm} is the evaporative fraction sensitivity to soil moisture; PBL is the PBL characteristics (including PBL height); ENT is the entrainment flux at the top of the PBL; T_{2m} and Q_{2m} are the 2-m temperature and humidity, respectively; and *P* is precipitation.

Outlying the pathways that define the SM-P relationship.

$$\Delta SM \underset{a}{\rightarrow} \Delta EF \underset{b}{\rightarrow} \Delta PBL \underset{c}{\rightarrow} \Delta Ent \underset{d}{\rightarrow} \Delta T_{2m}, Q_{2m} \Rightarrow \Delta P, \text{Cloud}. \quad (1)$$

From Santanello et al., 2018

Regional-to-local-scale forcing

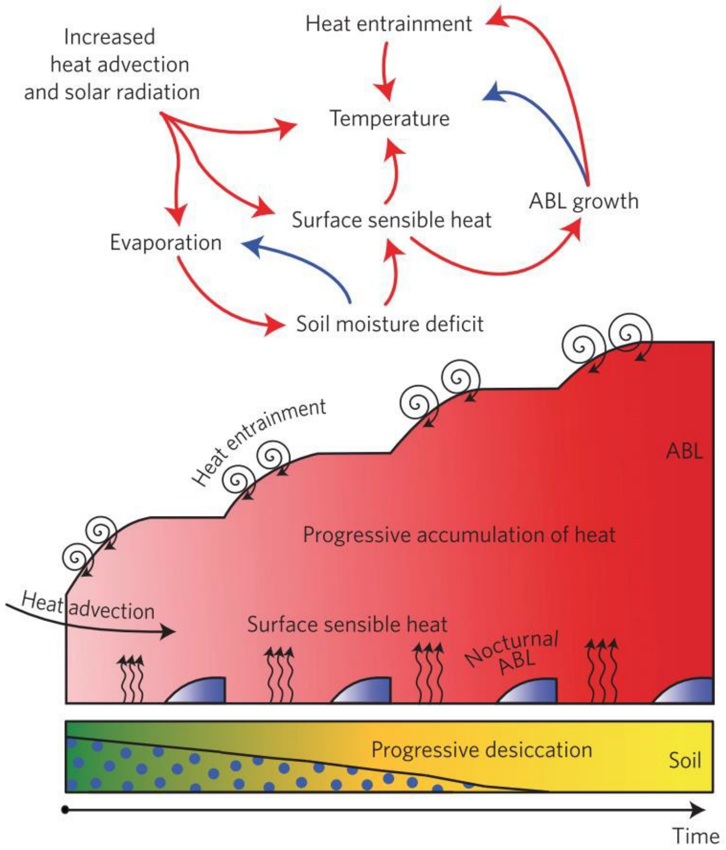


Figure 4 | Land–atmosphere interactions during mega-heatwaves revisited. Representation of the main soil moisture–air temperature interactions in the development of a mega-heatwave. Red and blue arrows represent positive and negative correlations, respectively.

Extreme temperature loop in mega-heatwave, land–atmosphere feedbacks leading to extreme temperatures exacerbation through a combined **multi-day memory of the land surface and PBL**.

From Miralles et al., 2014

Regional-to-local-scale forcing

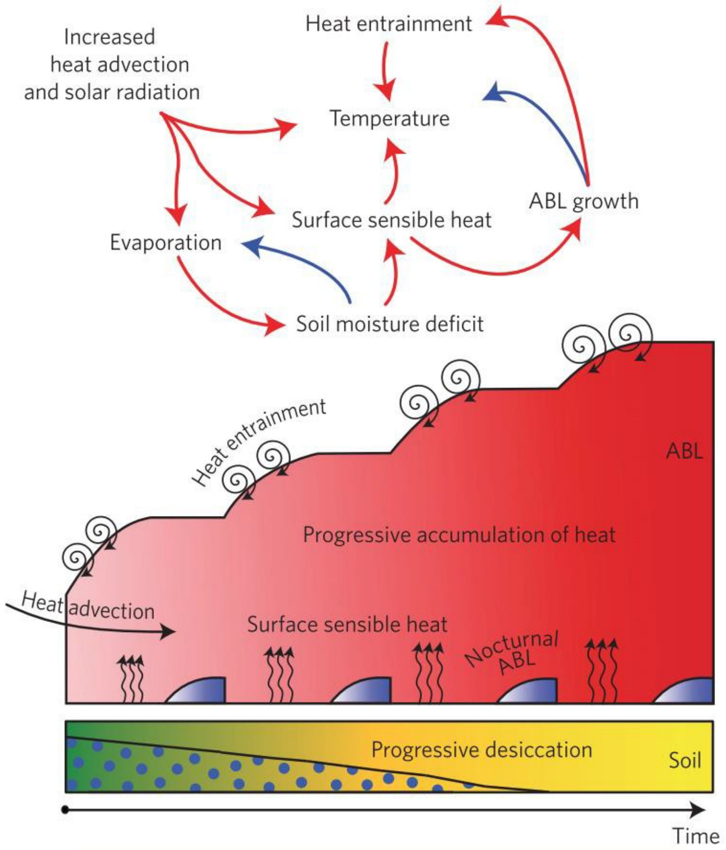


Figure 4 | Land–atmosphere interactions during mega-heatwaves revisited. Representation of the main soil moisture–air temperature interactions in the development of a mega-heatwave. Red and blue arrows represent positive and negative correlations, respectively.

Extreme temperature loop in mega-heatwave, land–atmosphere feedbacks leading to extreme temperatures exacerbation through a combined **multi-day memory of the land surface and PBL**.

This mechanism creates a **positive feedback loop (**under persistent high-pressure systems):
Drier soils → more sensible heat → deeper PBL → more entrainment of warm air → even higher temperatures near the surface.

From Miralles et al., 2014

SCEWERO

Heatwave analysis in regional context: challenges, available datasets, shortcomings

Lorenzo Sangelantoni

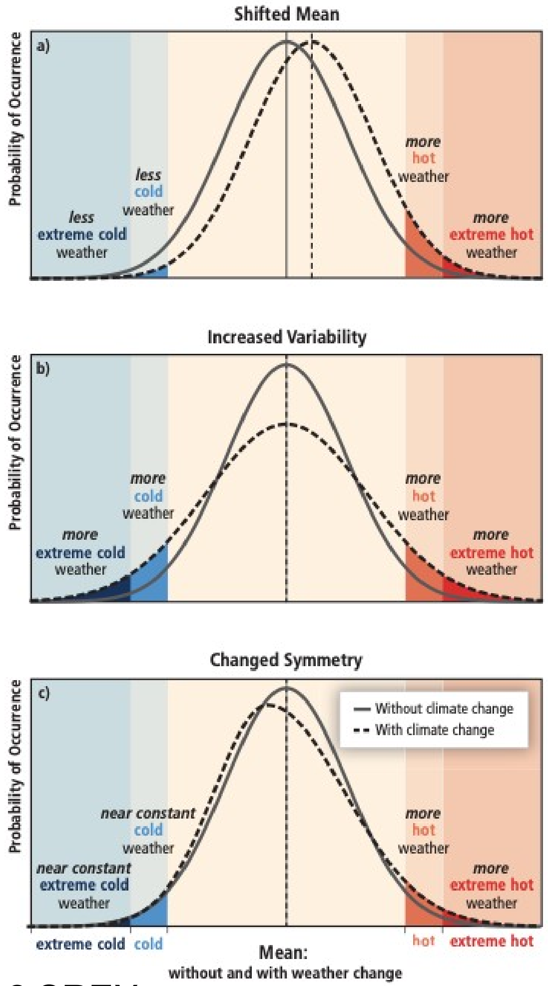
Funded by the European Union
Grant Agreement 101159497

Talk outline

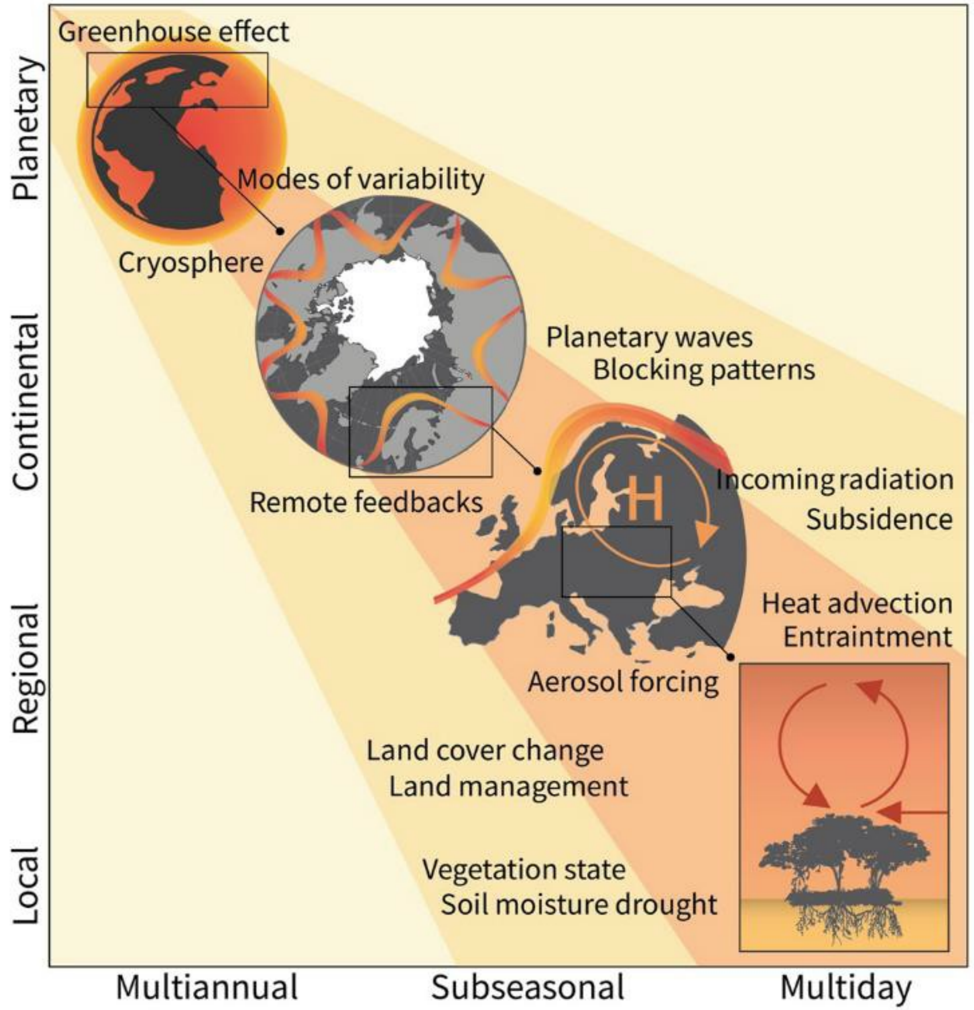
- **Heatwaves in a changing climate**
  - Regional pattern of changes in heatwaves;
  - Are climate model able to reproduce observed heatwave trends?
  - Main limitation/challenges.

- **Access to climate model simulations for heatwaves analysis**
  - CMIP6;
  - CORDEX;
  - ESGF;
  - Copernicus CDS.

HWs in a changing climate, from statistics to physics



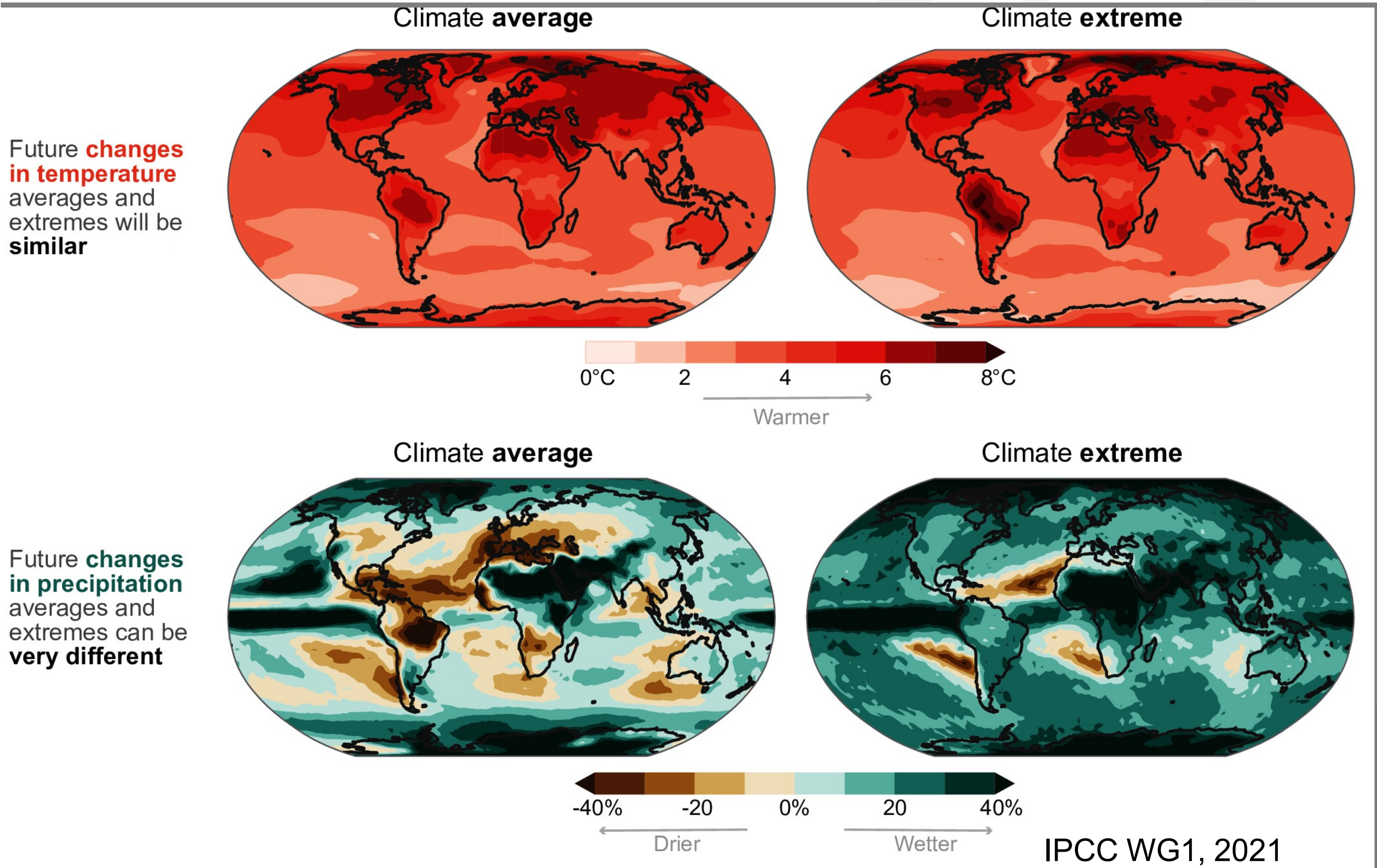
IPCC, 2012 SREX



Barriopedro et al., 2023

HWs in a changing climate

How will changes in climate extremes compare with changes in climate averages?

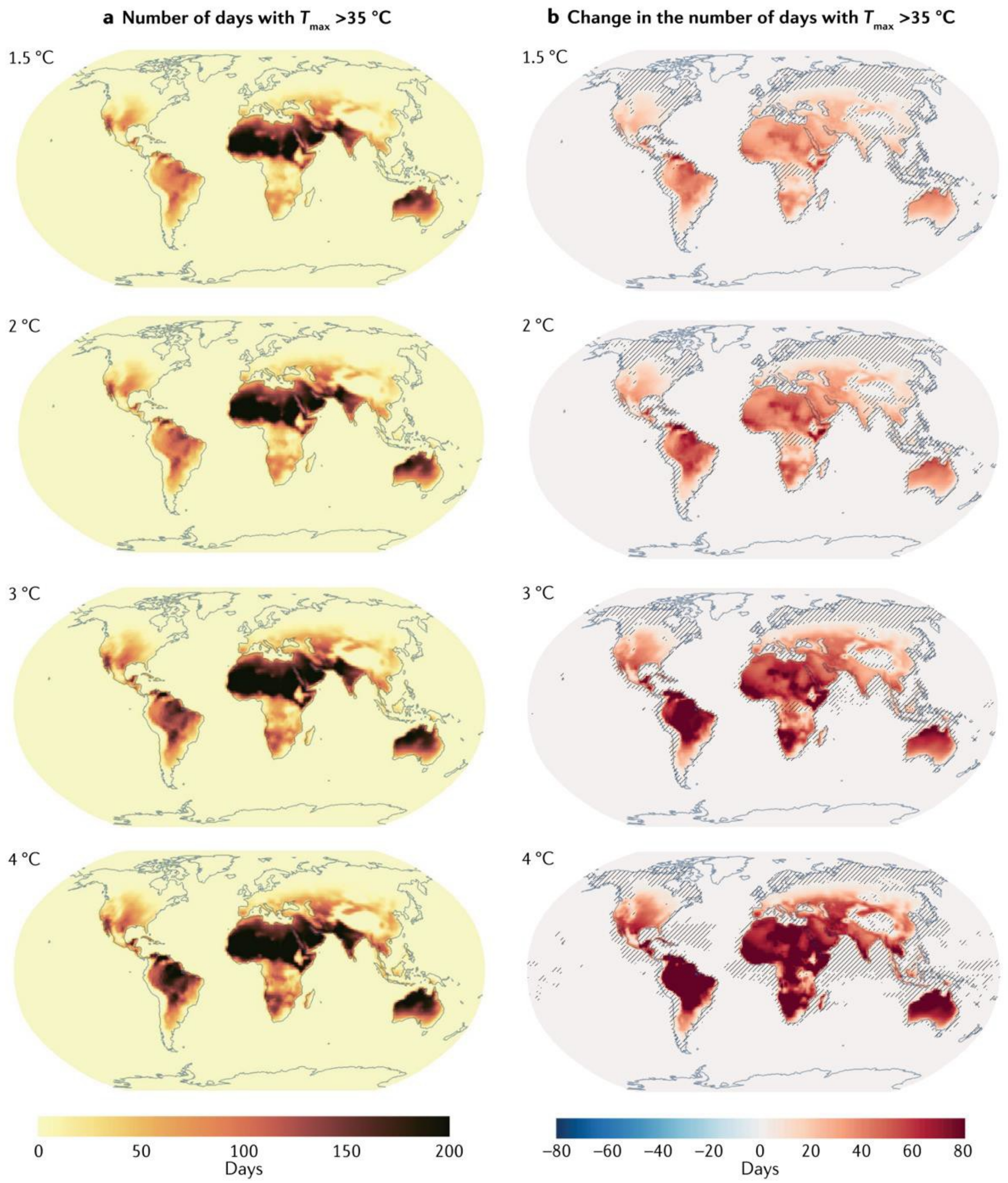


IPCC WG1, 2021

- **Regional** changes can outpace global mean temperatures.
- **Seasonal** changes can differ from annual mean changes.
- Changes can be different for different parts of the **distribution**.

CMIP6 ensemble median with a 4 °C GW wrt1850-1900. Extreme T2m refer to the hottest day of the year. Precipitation refers to the largest daily precipitation of the year

HWs in a changing climate



Occurrence of very hot days under different warming levels.

a) The projected number of days per year with maximum temperatures above 35 °C over land for (from top to bottom) warming levels of 1.5 °C, 2 °C, 3 °C and 4 °C. Warming levels represent average global temperatures relative to 1850–1900 from CMIP6 models from the SSP5-8.5 scenario.
b) Changes in the number of days per year with maximum temperatures above 35 °C over land with respect to the reference period 1850–1900. Hatching represents regions with low model agreement.

From Domenissen et al., 2023

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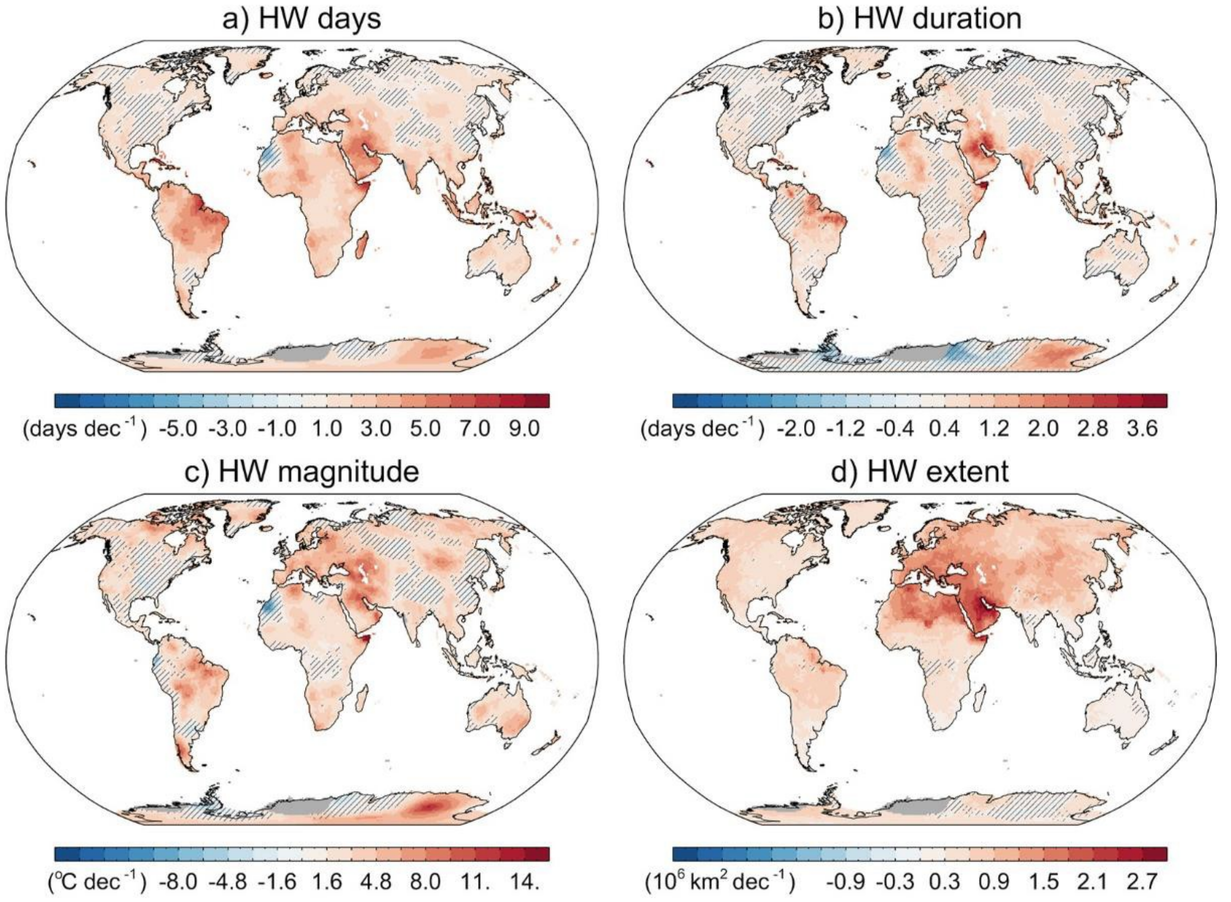
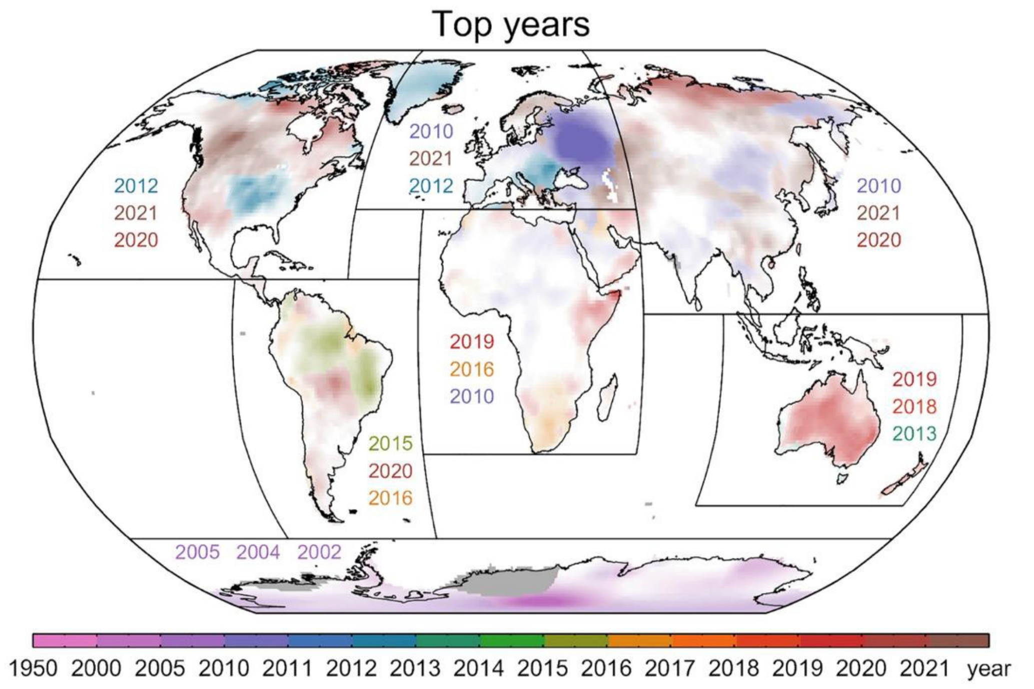
HWs in a changing climate

From Barriopedro et al., 2023

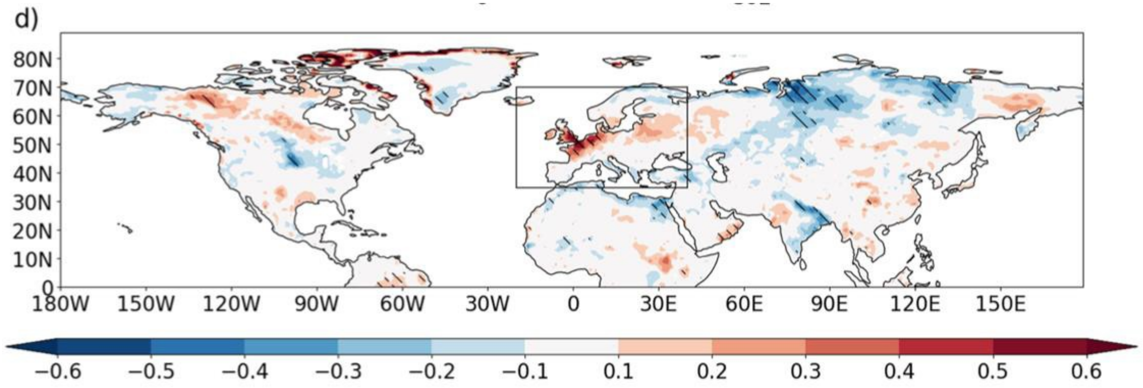


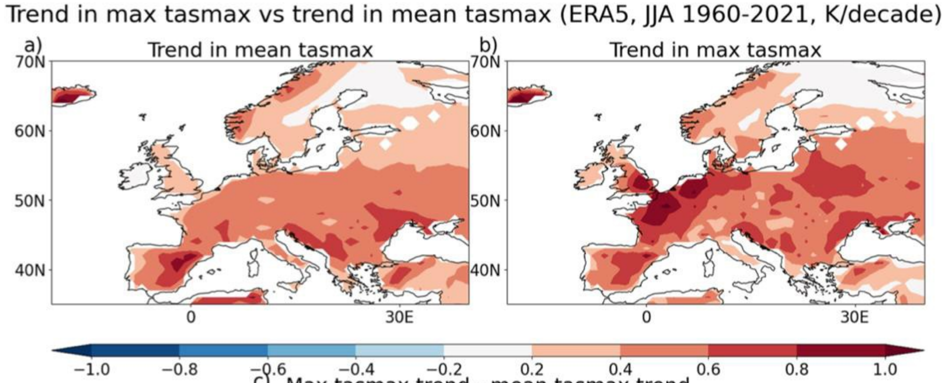
Trends (1950-2021) in warm-season HW features: (a) HW days frequency. (b) maximum HWs duration in the year. (c) HWs magnitude. (d) annual maximum areal extent

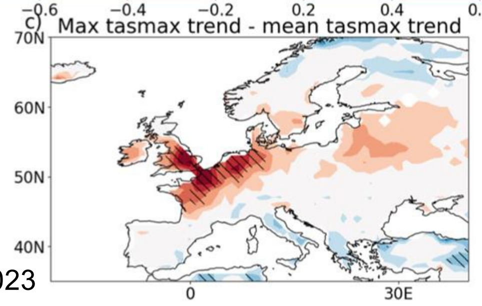


Top three years of the 1950-2021 period for each continent ranked by HW magnitude. Colors correspond to the year of occurrence.

HWs in a changing climate, the rapid European summer warming







From Patterson 2023

Global emergence of regional heatwave hotspots outpaces climate model simulations

Kai Kornhuber[a,b,c,1], Samuel Bartusek[b,d], Richard Seager[b], Hans Joachim Schellnhuber[a,1], and Mingfang Ting[b,c]

North-West Europe Hottest Days Are Warming Twice as Fast as Mean Summer Days

Matthew Patterson[1]

Acceleration of daily land temperature extremes and correlations with surface energy fluxes

Check for updates

Chris Huntingford[1], Peter M. Cox[2,3], Paul D. L. Ritchie[2,3], Joseph J. Clarke[2], Isobel M. Parry[2] & Mark S. Williamson[2,3]

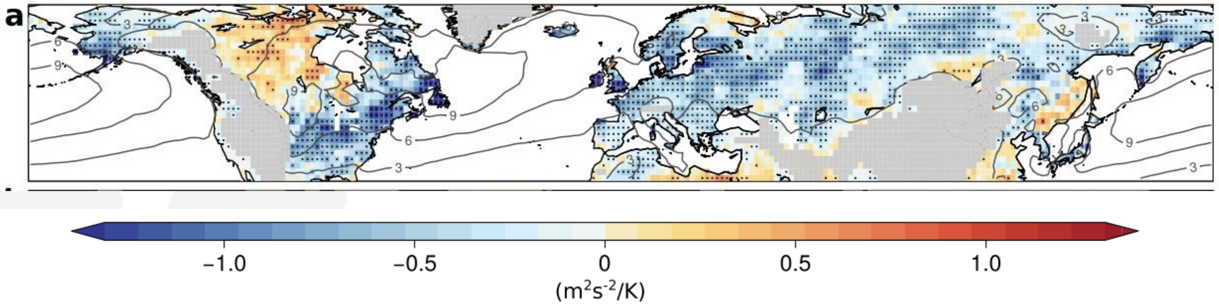
Weakening of the NH summer circulation

The weakening summer circulation in the Northern Hemisphere mid-latitudes

Dim Coumou,[1*] Jascha Lehmann,[1,2] Johanna Beckmann[1,2]

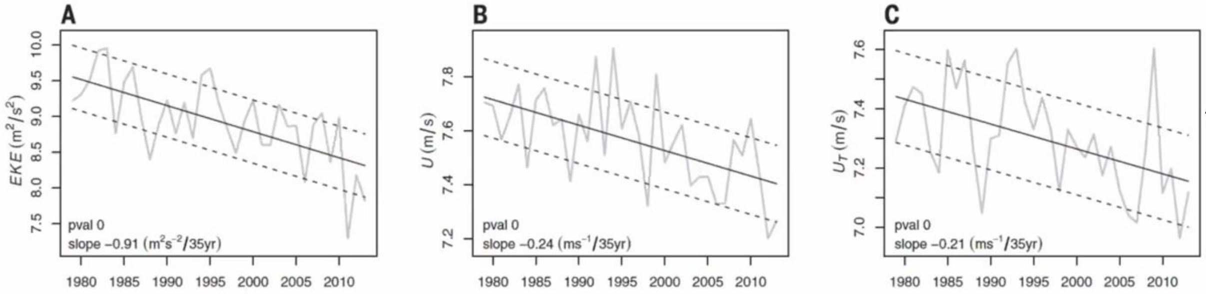
Rapid warming in the Arctic could influence mid-latitude circulation by reducing the poleward temperature gradient. The largest changes are generally expected in autumn or winter, but whether significant changes have occurred is debated. Here we report significant weakening of summer circulation detected in three key dynamical quantities: (i) the zonal-mean zonal wind, (ii) the eddy kinetic energy (EKE), and (iii) the amplitude of fast-moving Rossby waves. Weakening of the zonal wind is explained by a reduction in the poleward temperature gradient. Changes in Rossby waves and EKE are consistent with regression analyses of climate model projections and changes over the seasonal cycle. Monthly heat extremes are associated with low EKE, and thus the observed weakening might have contributed to more persistent heat waves in recent summers.

Slope of quantile regression between anomalies of EKE and temperature in summer (p90)



From Lehmann & Coumou 2015

Hottest summer months are associated with low EKE



Absolute changes in (A) EKE, (B) zonal wind U, and (C) thermal wind UT over 1979–2013 in summer. Variables are calculated at 500 mb and averaged over 35°N to 70°N and all longitudes, with grey lines plotting observations, solid black lines the linear trend.

From Coumou et al., 2015

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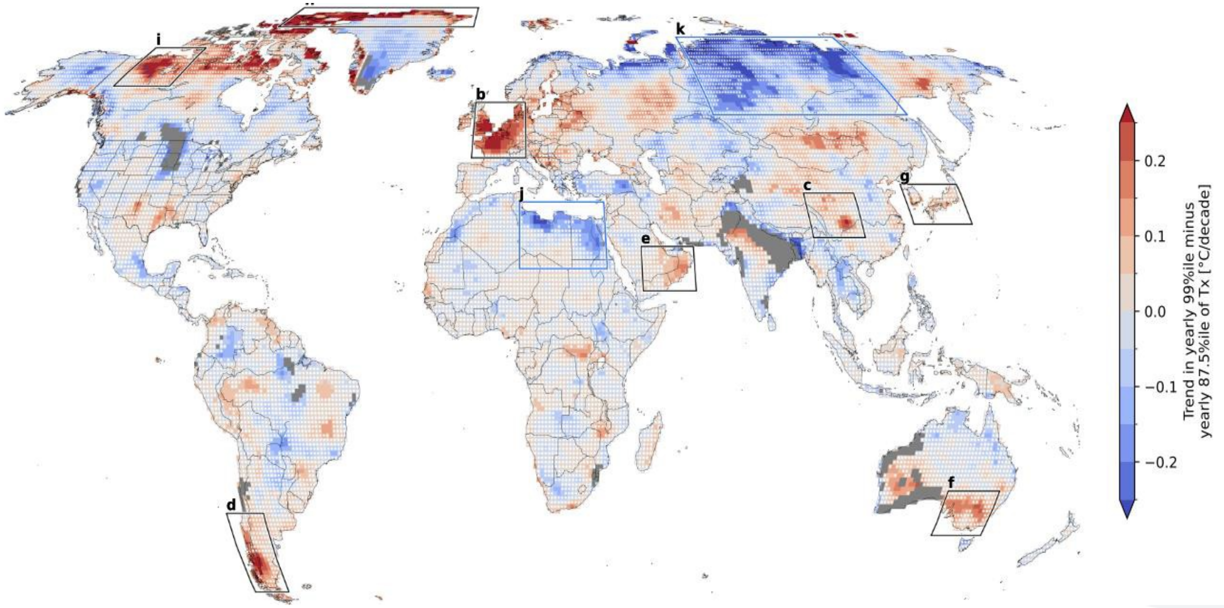
Are climate models able to reproduce regional patterns of accelerated summer season warming?

Trend in extreme heat tail-widening (p99-p87.5)



From Kornhuber et al., 2024

Regional trends in **extreme heat tail-widening**, estimated by calculating long-term **trends in the differences of the yearly 99th** percentile of daily maximum temperature (Tx) **and the yearly 87.5th** percentile of Tx (the median of the upper quartile bounded by the 75th and 100th percentiles) at each grid-point over 1958 to 2022.

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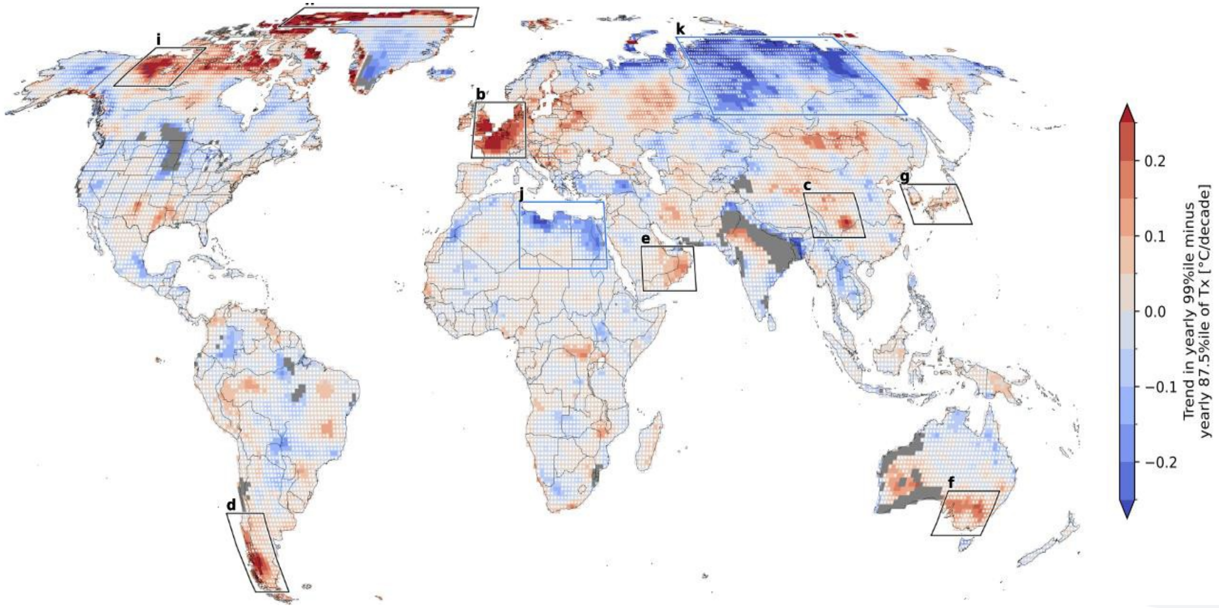
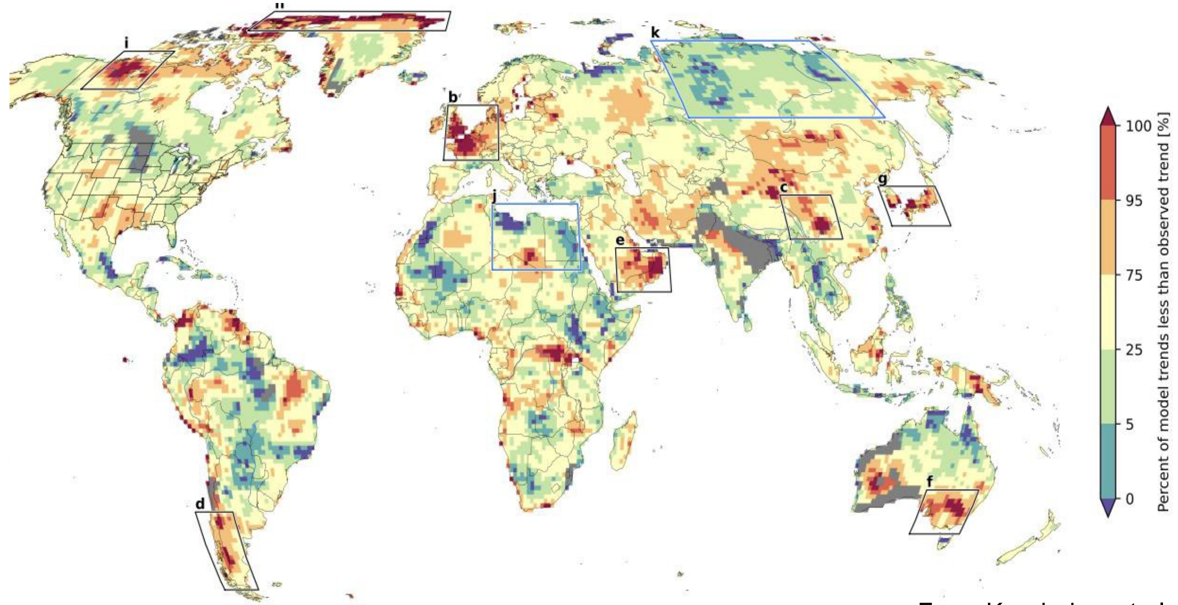


Percentage of models underestimating extreme heat tail-widening



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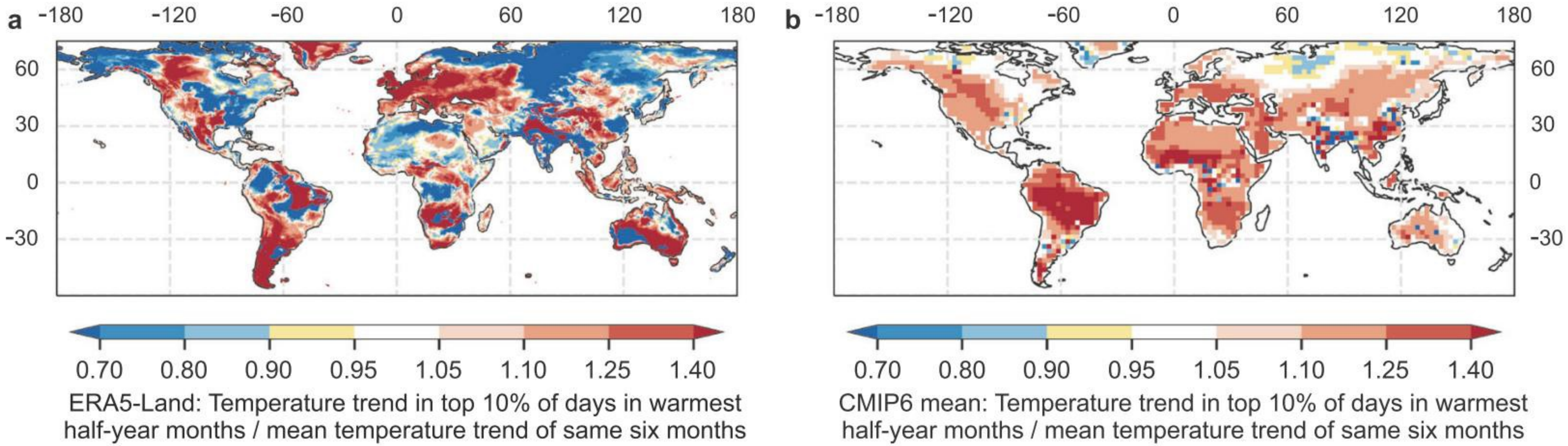
HWs in a changing climate, globally emerging HW hotspots



Trends for land points from the ERA5-Land and CMIP6 subset ensemble data for the years 1950–2021. Trends are of the warmest half-year months and the warmest 10% of days within those 6 months.

From Huntingford et al., 2024

What's wrong in GCMs?

Heat extremes in Western Europe increasing faster than simulated due to atmospheric circulation trends

Vautard et al., 2023

circulation changes shows that there is a large dynamical contribution to this observed trend, which is underestimated in all the 170 climate simulations analyzed, explaining a large part of the discrepancy in trend between models and observations. By contrast, models and observational trends are broadly consistent in terms of the thermodynamic contribution to the trend in mean temperatures. Although it

Summertime Rossby waves in climate models: substantial biases in surface imprint associated with small biases in upper-level circulation

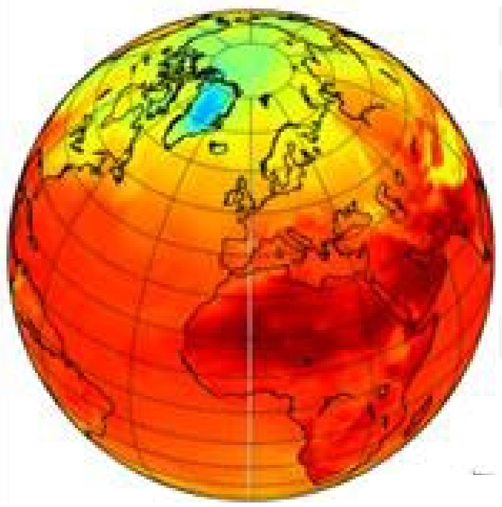
Luo et al., 2022

cesses. Focusing on wave 5 and wave 7, we show that while the wave's position and magnitude are generally well represented during high-amplitude (> 1.5 SD) episodes, the associated surface anomalies are substantially underestimated.

Representation of summer temperature and HWs in RCMs

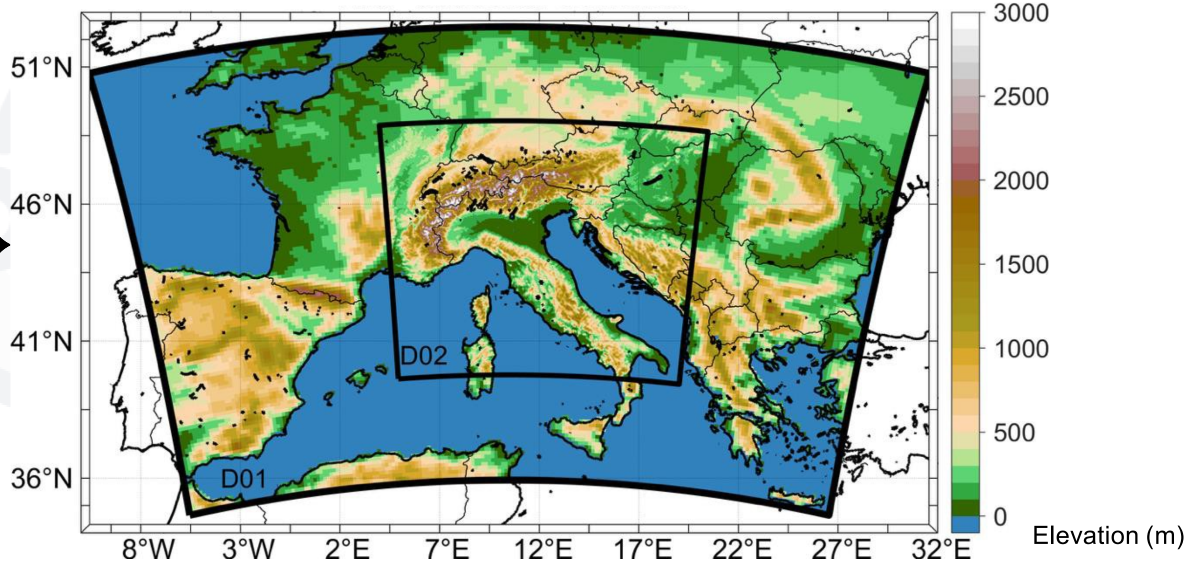
Dynamical downscaling

Global climate model or reanalysis providing initial and boundary conditions for the nested regional climate model(s)



→

Nested RCMs – WRF 15 km | WRF 3 km

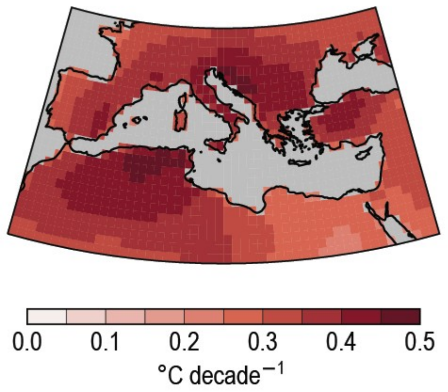


Sangelantoni et al., 2023

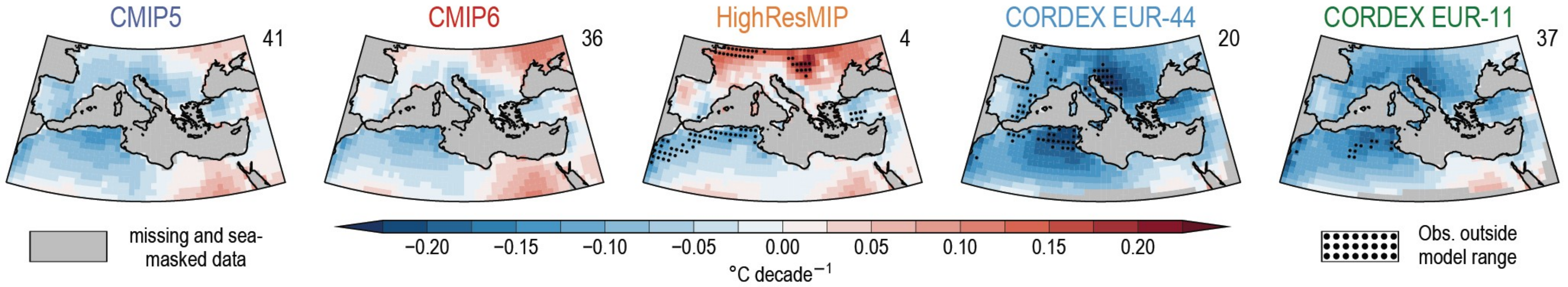
Representation of summer temperature and HWs in RCMs

Summer surface air temperature trends

(d) Observed trend (BerkeleyEarth)
Past period (1960-2014)



(g) Ensemble mean trend differences with respect to the observed trend ((d), 1960-2014)



IPCC AR6 2021 chap. 10

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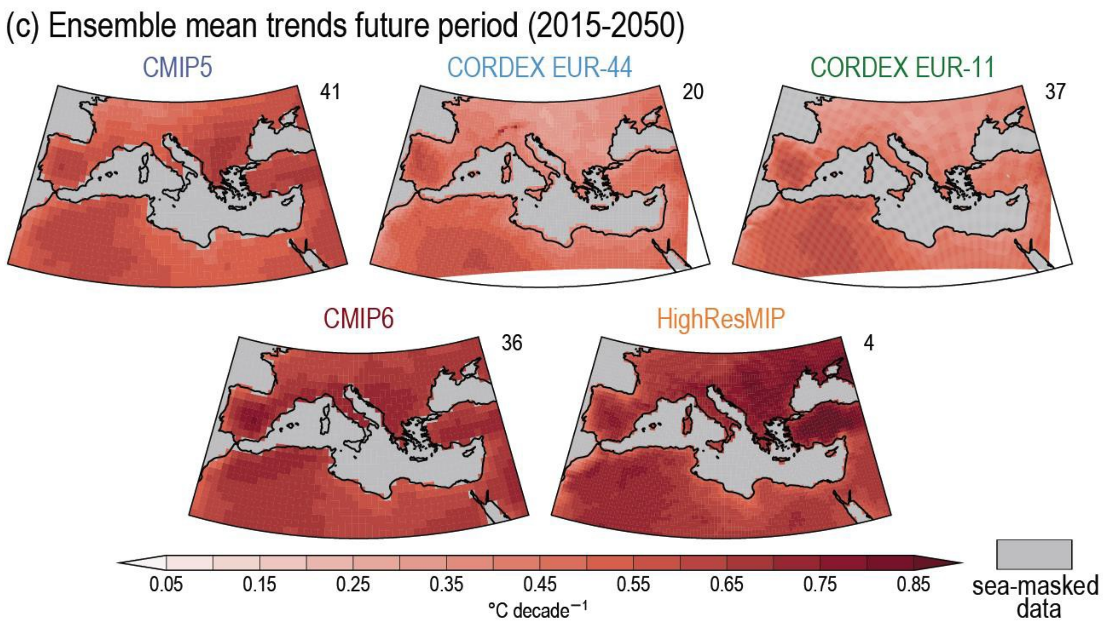
Representation of summer temperature and HWs in RCMs

Future summer season change signal in RCMs vs. GCMs



IPCC AR6 2021 chap. 10

Representation of summer temperature and HWs in RCMs

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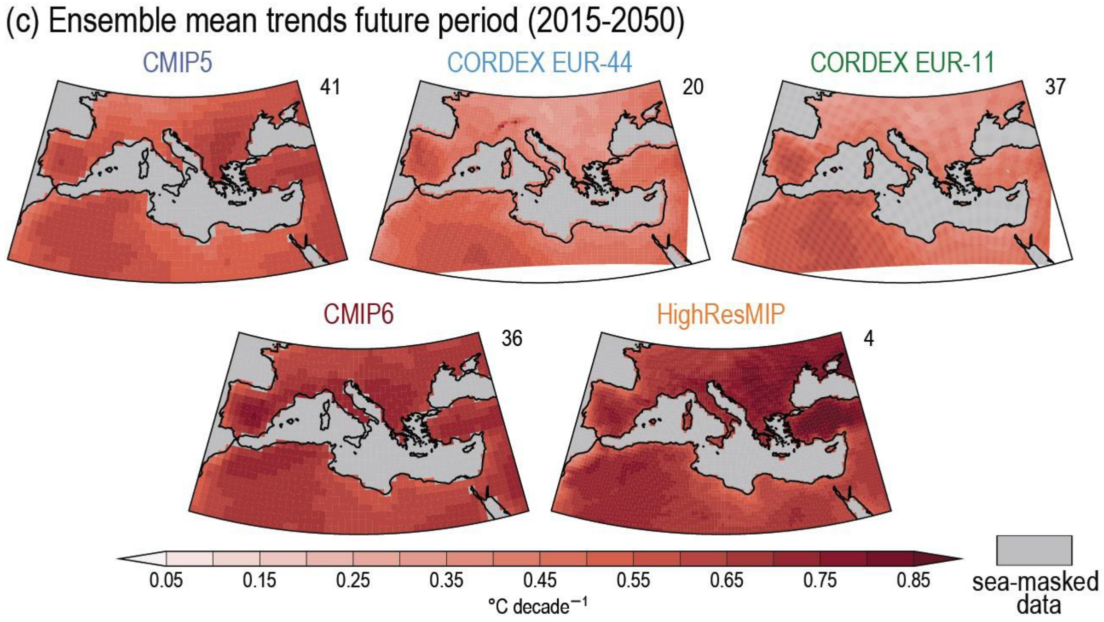
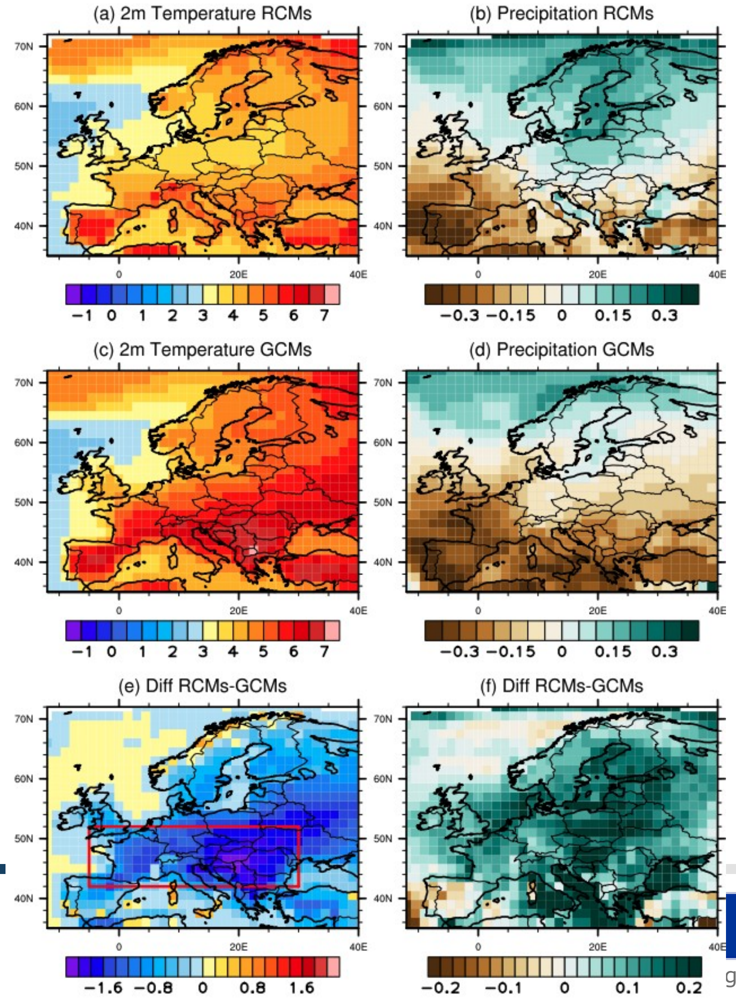


IPCC AR6 2021 chap. 10



Ensemble mean changes in summer temperature (K) and relative precipitation over Europe between 2070–2099 and 1970–1999

Boé et al., 2020

SCEWERO

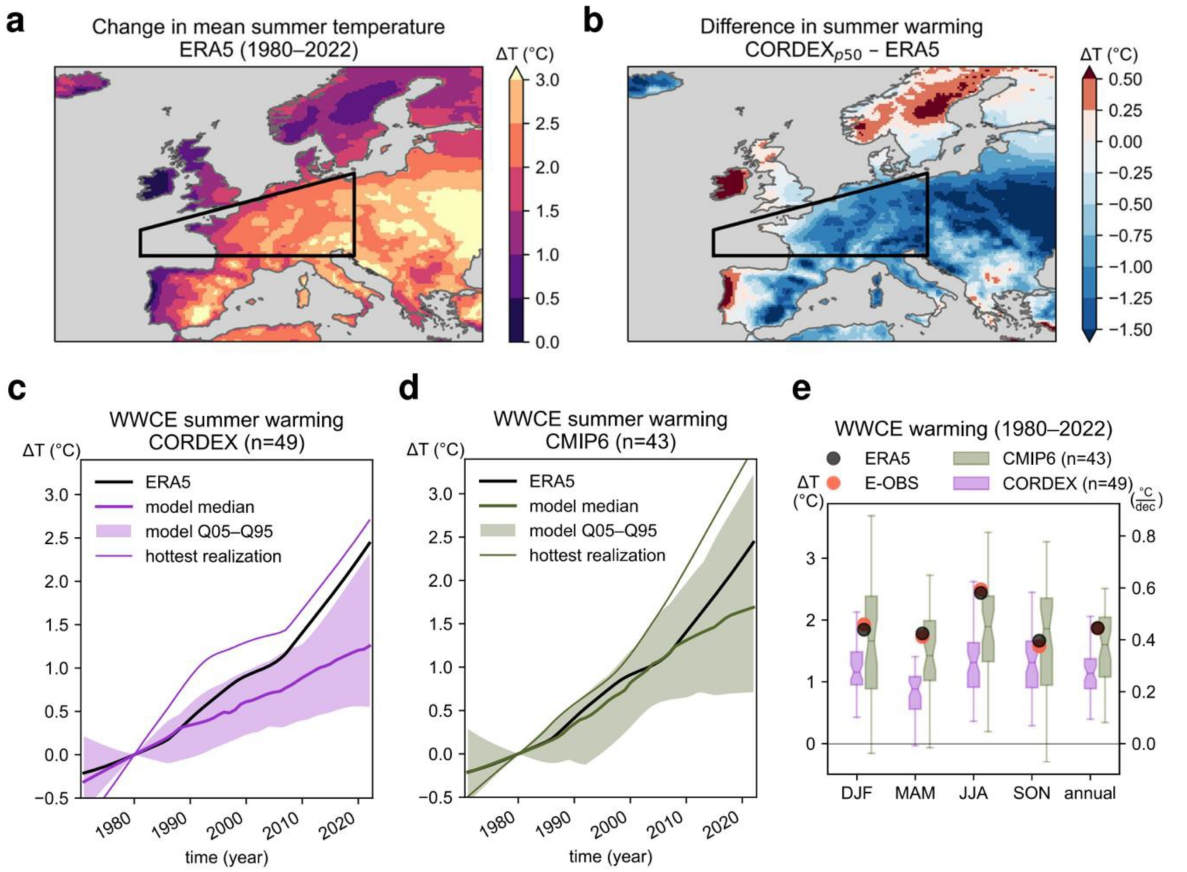
STRENGTHENING THE RESEARCH CAPACITIES FOR EXTREME WEATHER EVENTS IN ROMANIA

What possibly wrong in RCMs?

Exacerbated summer European warming not captured by climate models neglecting long-term aerosol changes

Check for updates

Dominik L. Schumacher, Jitendra Singh, Mathias Hauser, Erich M. Fischer, Martin Wild & Sonia I. Seneviratne



The CORDEX multimodel mean has been found to underestimate the observed increase in downward shortwave radiation, since most RCMs do not consider time-evolving aerosols.

From Schumacher et al., 2024

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Datasets available for HWs analysis

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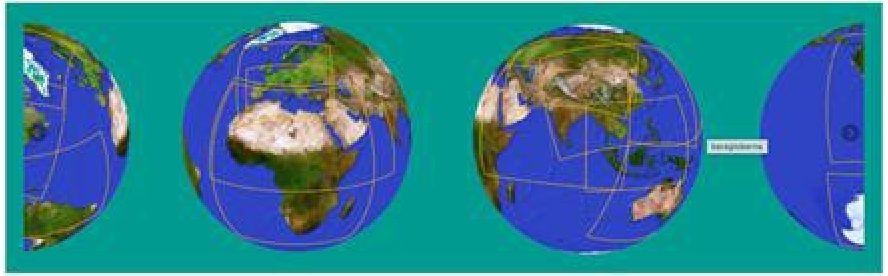
Coupled Model Intercomparison Project (CMIP)

Under the World Climate Research Programme (WCRP) the Working Group on Coupled Modelling (WGCM) established the **Coupled Model Intercomparison Project** (**CMIP**) as a standard experimental protocol for studying the output of coupled atmosphere-ocean General Circulation Models (AOGCMs).

Models results are used to perform research of relevance to climate scientists preparing the **Intergovernmental Panel on Climate Change Asssessment Reports (IPCC-AR)**

CORDEX AND EURO-CORDEX

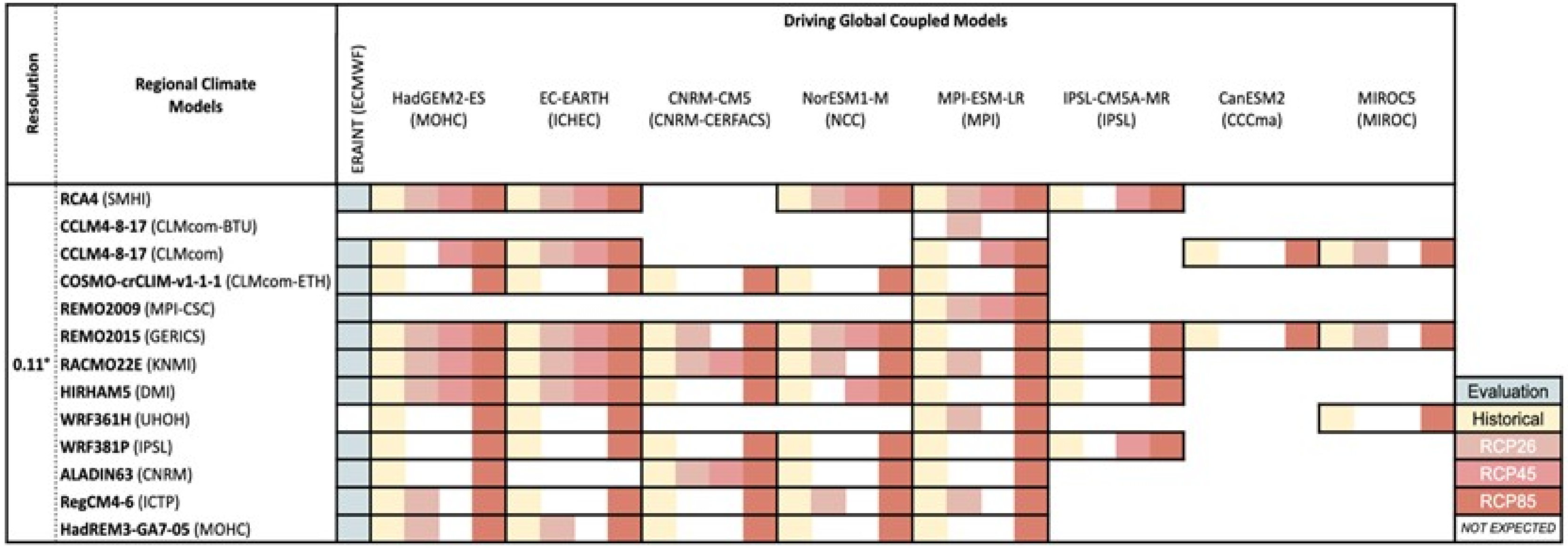
Guidance for EURO-CORDEX



Coordinated Regional Climate Downscaling Experiment

Provides ensembles of high resolution historical and future climate projections for various regions of the globe dynamically downscaling a set of CMIP5 GCMs. RCMs in CORDEX typically have a horizontal resolution ranging from 50 to 10 km.

EURO-CORDEX:



ESGF

Earth System Grid Federation

An open source effort providing a robust, distributed data and computation platform, enabling world wide access to Peta/Exa-scale scientific data.

ESGF Mission

The Earth System Grid Federation (ESGF) is an international collaboration for the software that powers most global climate change research, notably assessments by the Intergovernmental Panel on Climate Change (IPCC).

ESGF manages the first-ever decentralized database for handling climate science data, with multiple petabytes of data at dozens of federated sites worldwide. It is recognized as the leading infrastructure for the management and access of large distributed data volumes for climate change research. It supports the Coupled Model Intercomparison Project (CMIP), whose protocols enable the periodic assessments carried out by the IPCC.

Using a system of geographically distributed peer nodes—independently administered yet united by common protocols and interfaces—the ESGF community holds the premier collection of simulations and observational and reanalysis data for climate change research. —

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ESGF - NODES

esgf.github.io/nodes.html

ESGF About Documents Press Software Users Developers Nodes Docs/Wikis

Federated ESGF Nodes

Metagrid Nodes

These sites run the React-based Metagrid Web Application

- ANL
- DKRZ
- LLNL
- ORNL
- NCI

CoG Nodes

These sites run the *legacy* Django-based CoG Web Application. Please note that OpenID logins do not work on several of these systems.

- CEDA
- IPSL
- LIU

https://esgf-node.cels.anl.gov/

https://esgf-node.llnl.gov/

https://esgf-metagrid.cloud.dkrz.de/

https://esgf-node.ornl.gov/

https://esgf.nci.org.au/

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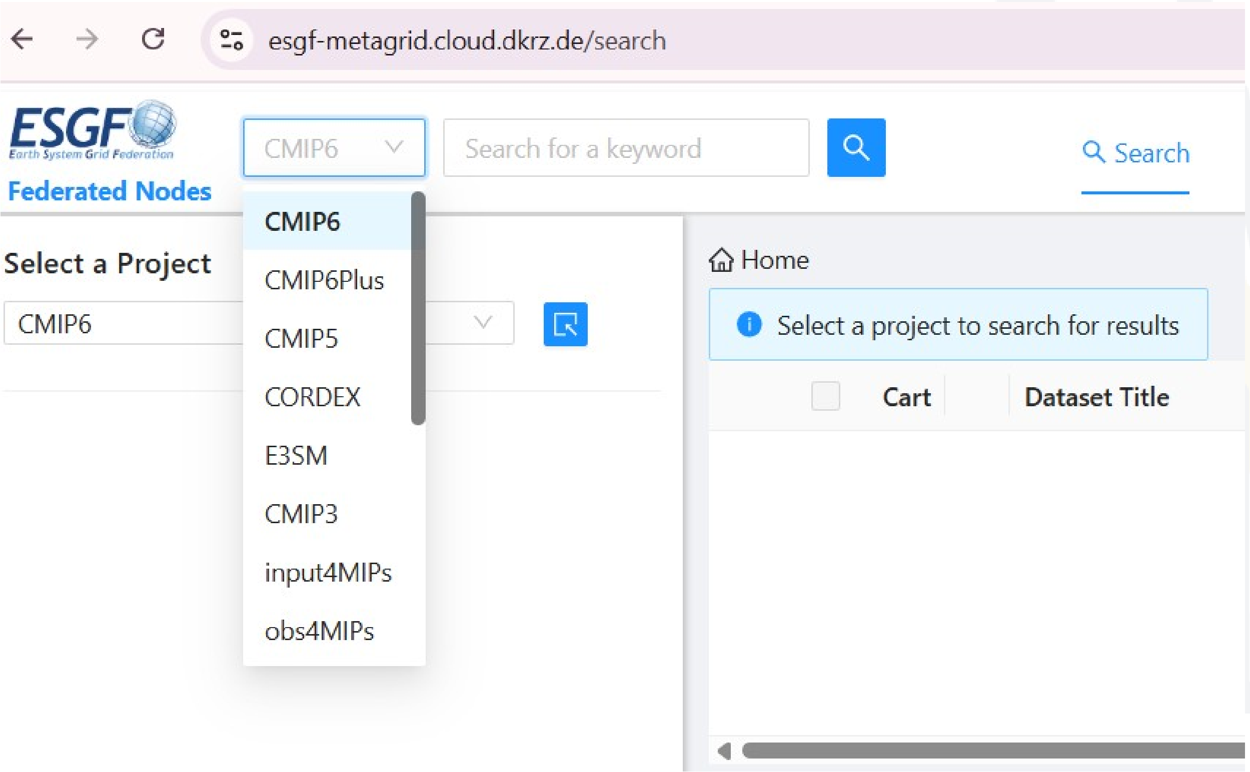
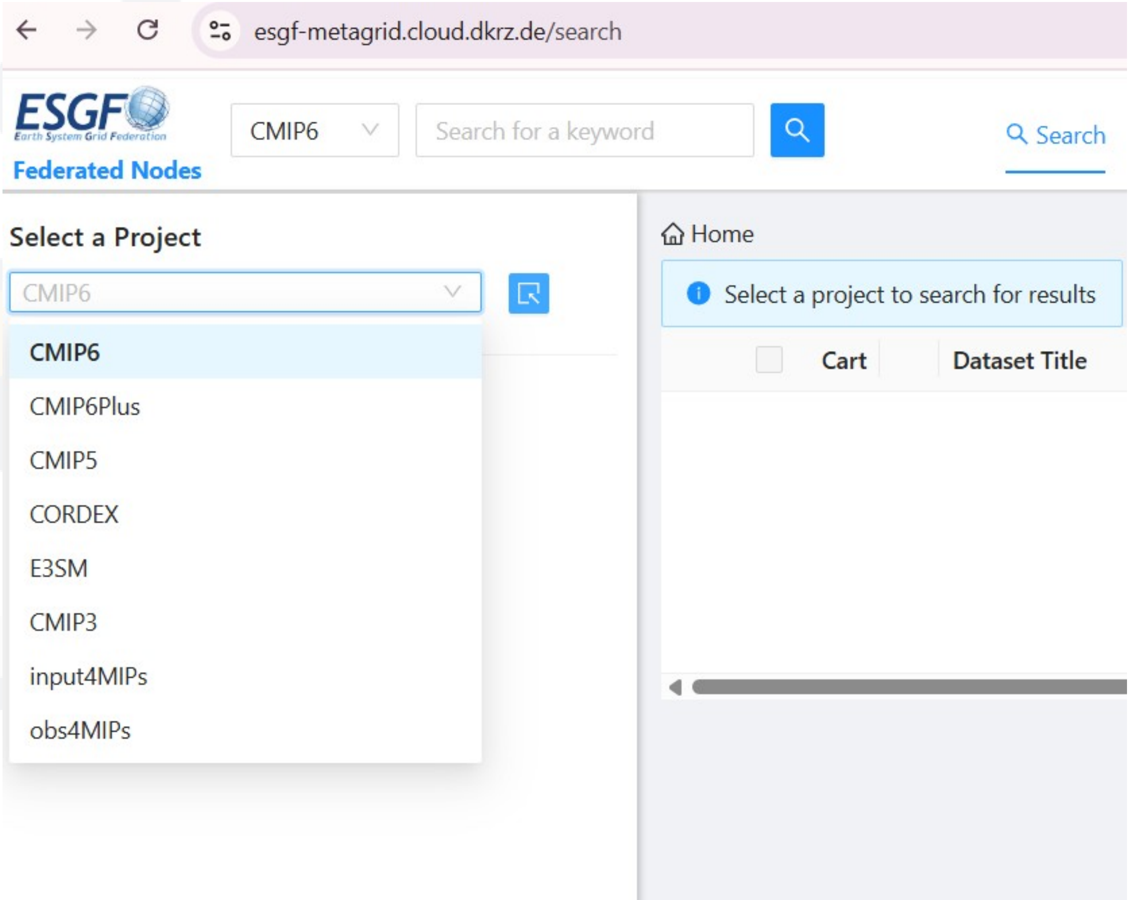
Navigating through ESGF - MetaGrid

Start by selecting the project (e.g., CMIP6, CORDEX). Note that slight differences in the interface may exist depending on the node. We selected CMIP6





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Navigating through ESGF - MetaGrid

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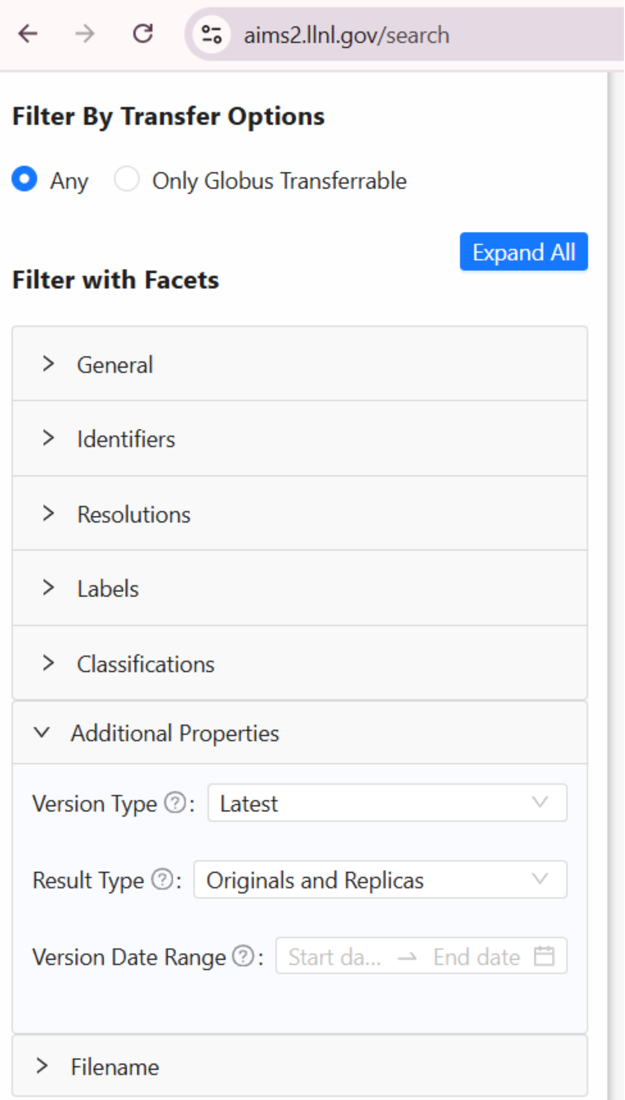

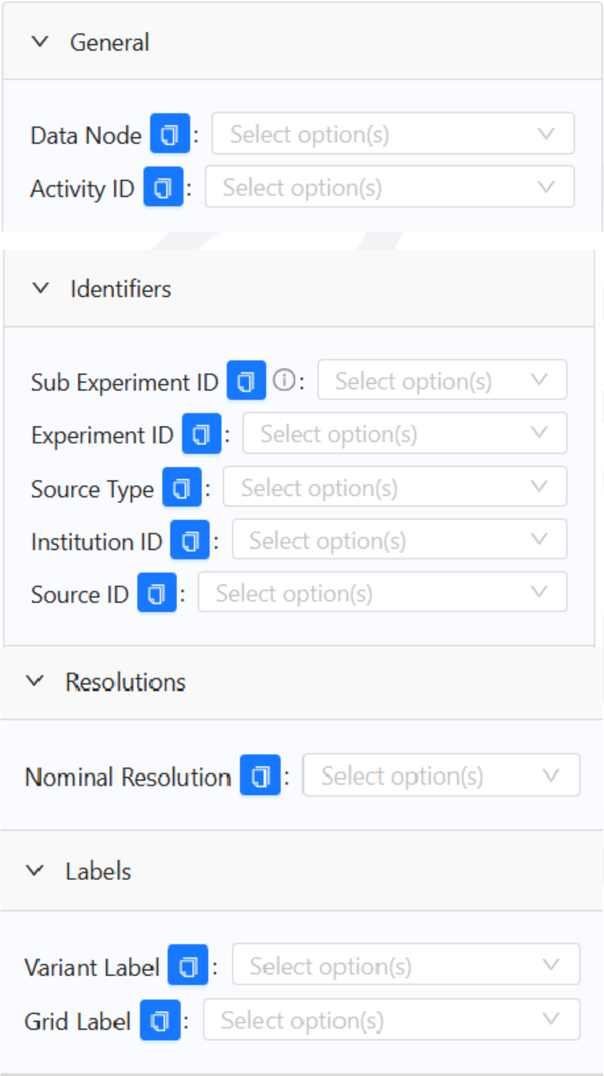

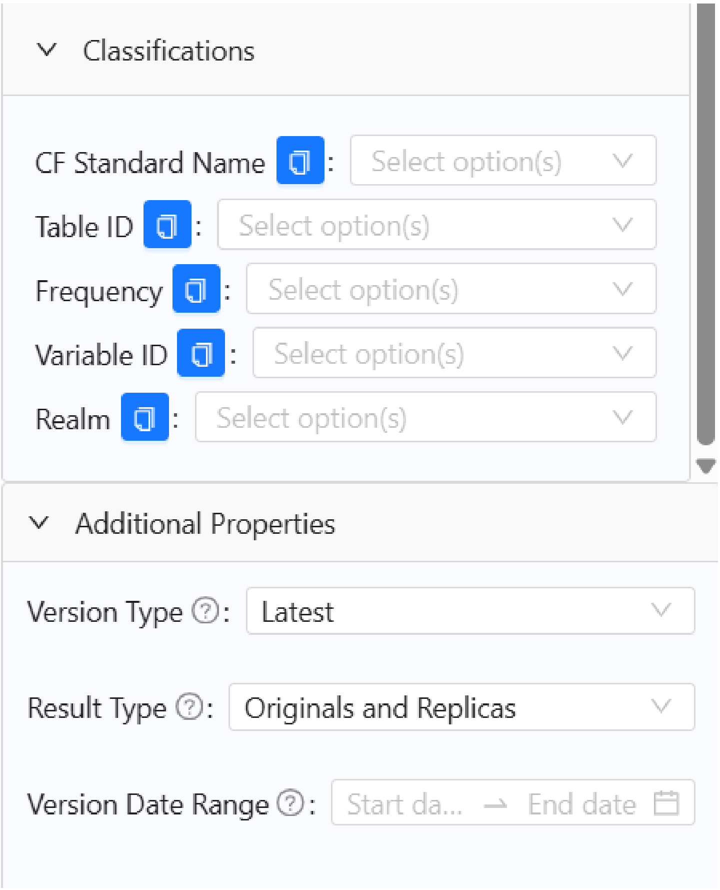

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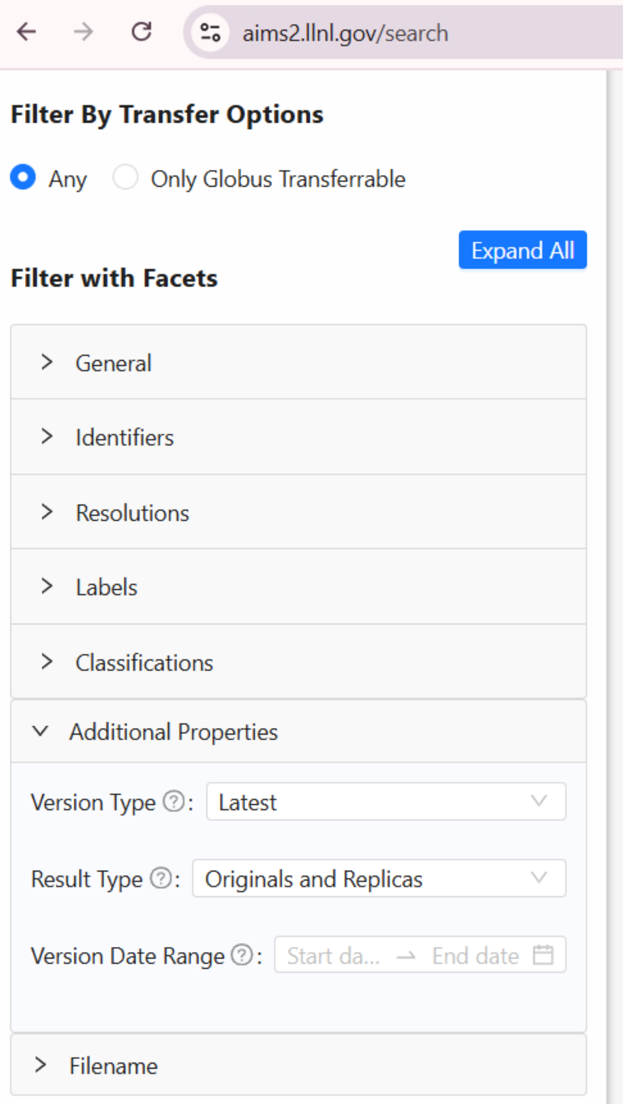
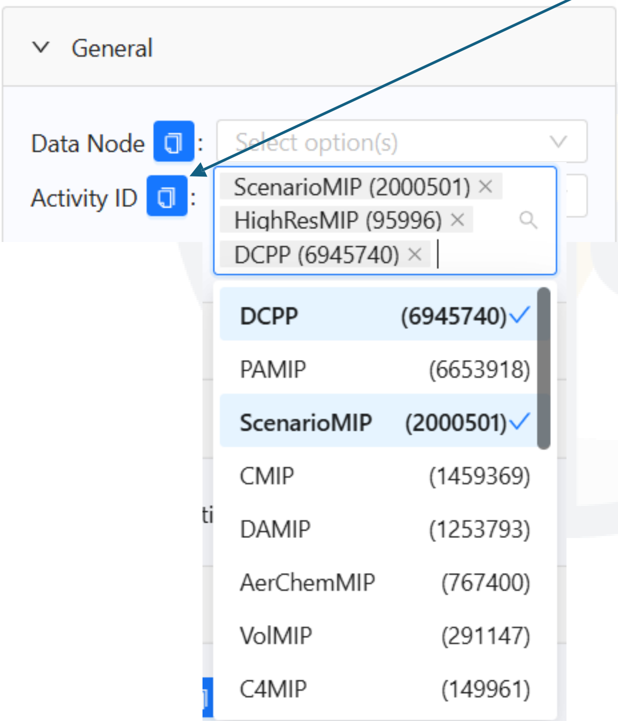
SCEWERO

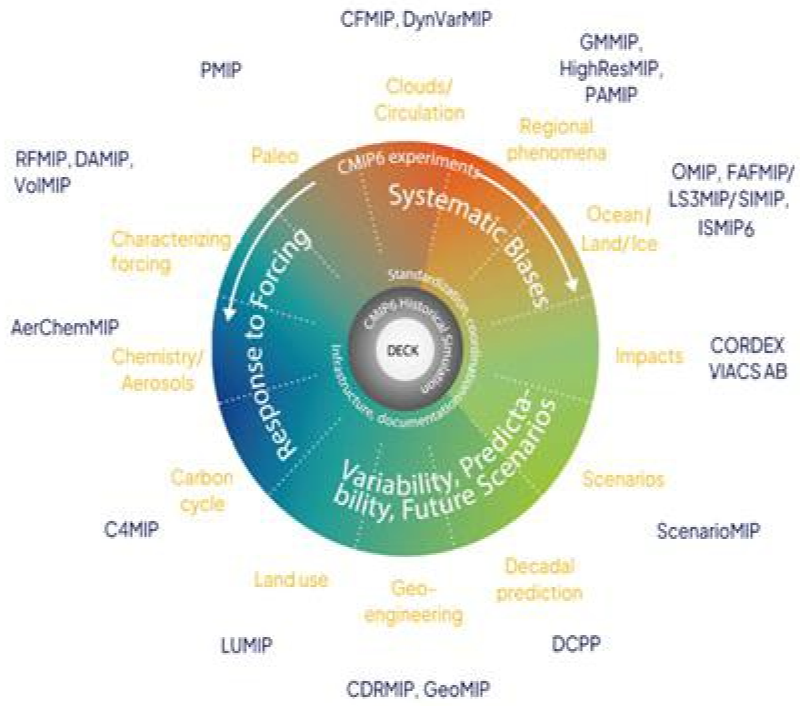
Navigating through ESGF - MetaGrid

STRENGTHENING THE RESEARCH CAPACITIES FOR EXTREME WEATHER EVENTS IN ROMANIA



Start by selecting the **ACTIVITY ID** (e.g., ScenarioMIP, HighResMIP,DCPP…). Keep in mind that not all models are available on every ESGF data node — this is particularly true for CORDEX. However, each MetaGrid web interface (e.g., https://esgf-metagrid.cloud.dkrz.de/search) provides access to the entire ESGF network, allowing you to browse and download data from all nodes regardless of where you start.





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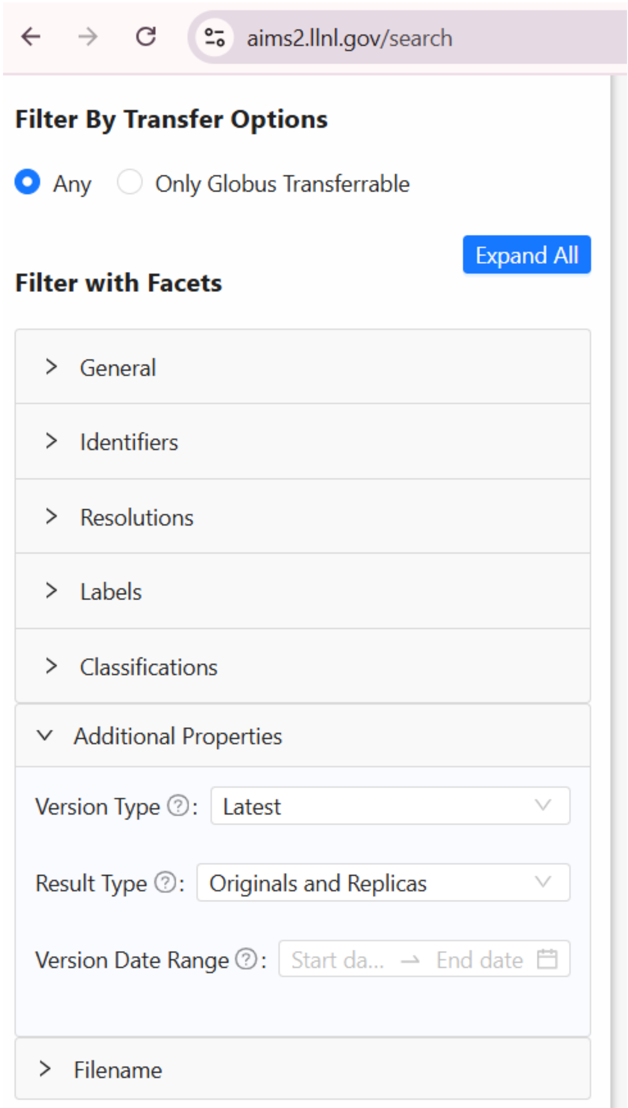
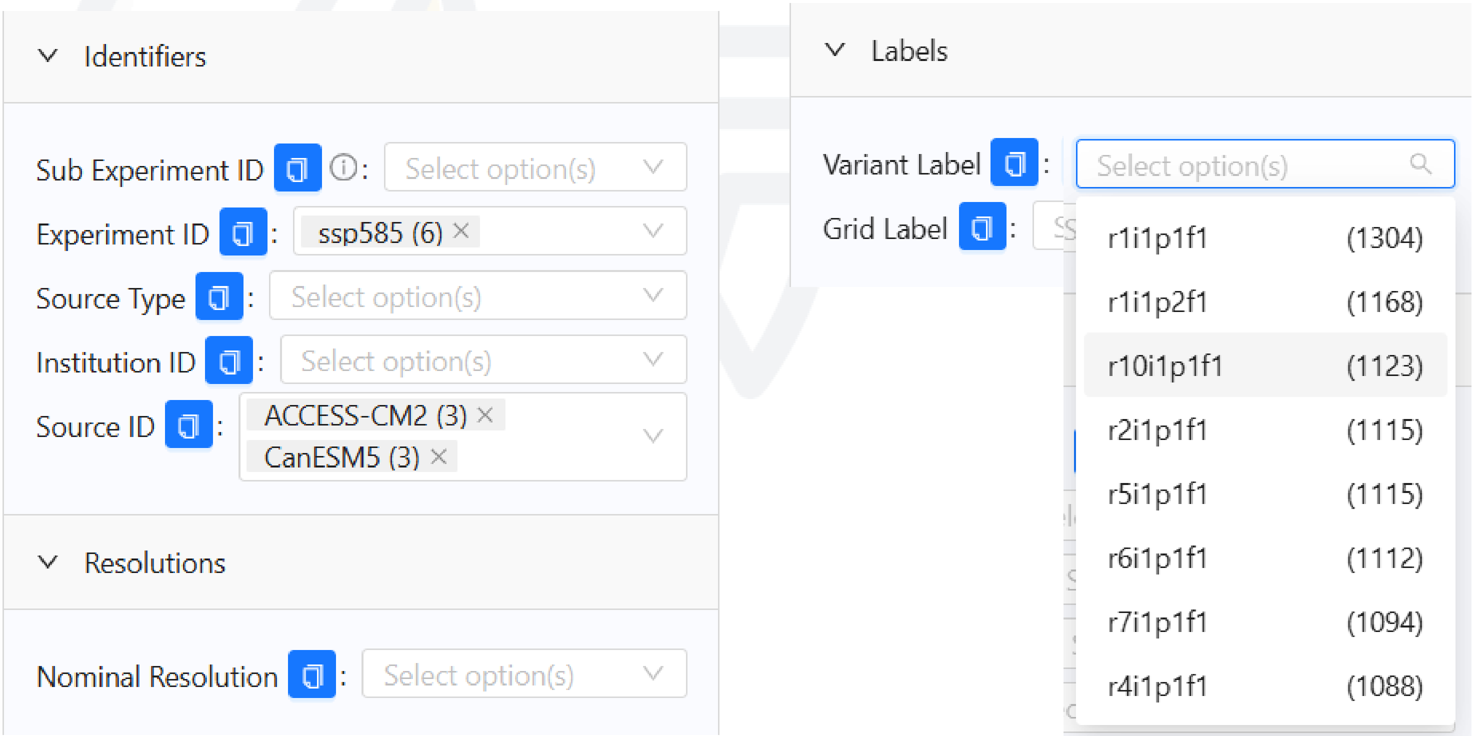
Navigating through ESGF - MetaGrid



Once selected the **ACTIVITY ID,** ScenarioMIP for our case we will have to select the EXPERIMENT ID and the SOURCE ID.

After the ensemble member can be selected (sometimes the model only provides a single member). **r, p, and f** gives info about the realization, the physics and the forcings.



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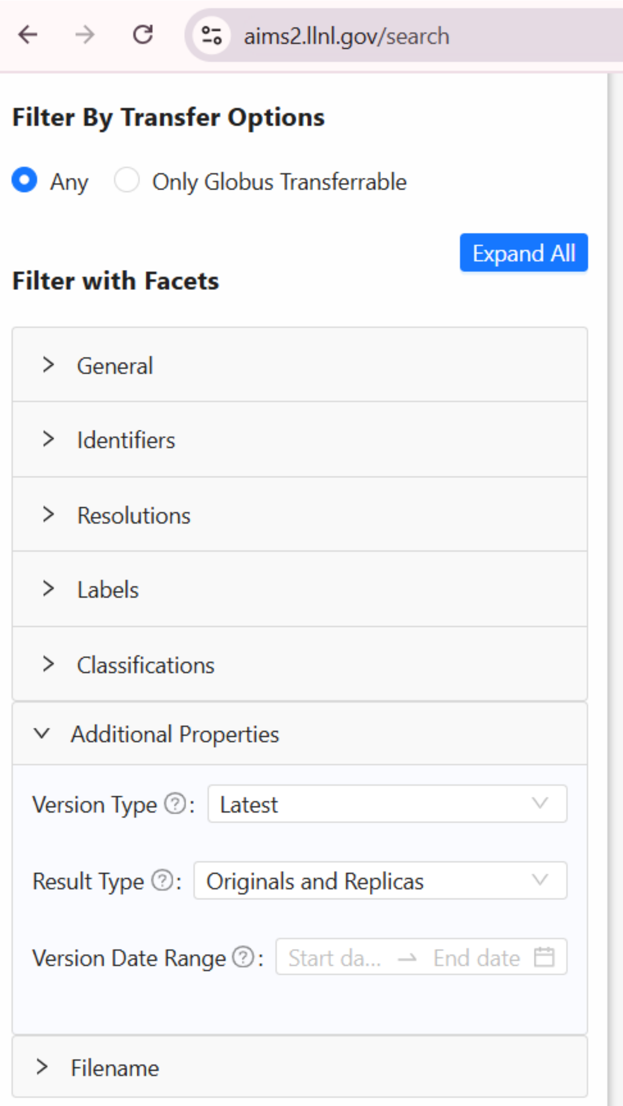
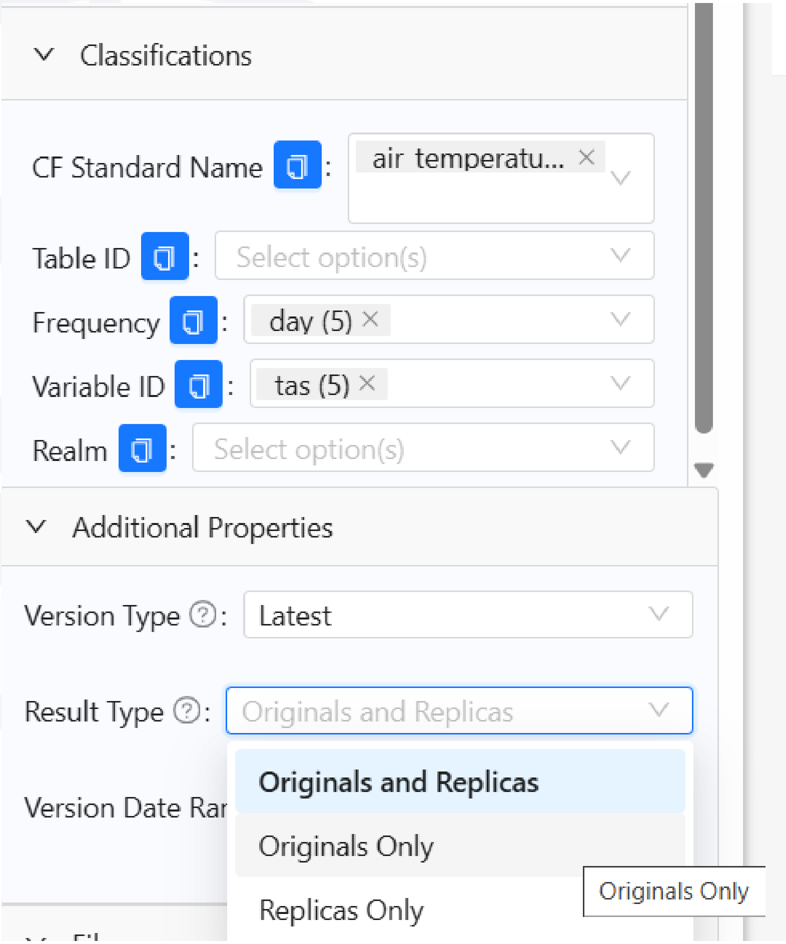
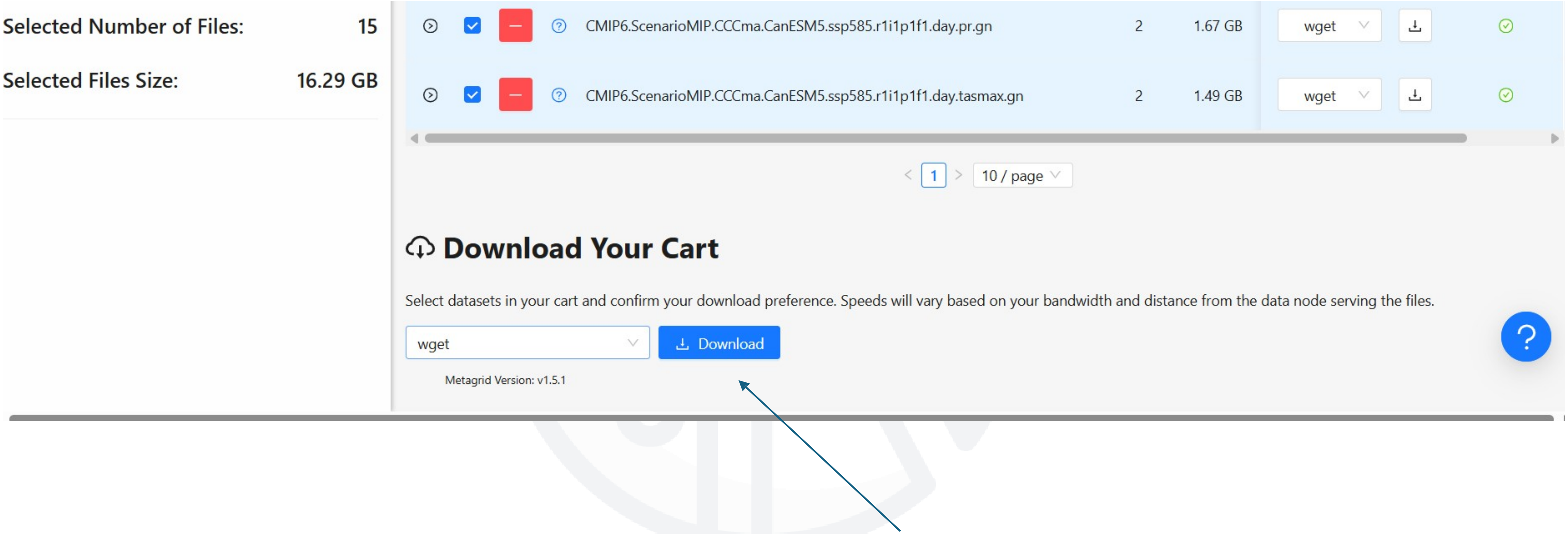
Navigating through ESGF - MetaGrid



Finally, you can also filter by temporal frequency, variable name, and whether to display only original datasets or include replicas.



Navigating through ESGF - MetaGrid



Finally you can download your selected files with GLOBUS or get a wget script

Download data from wget in bash

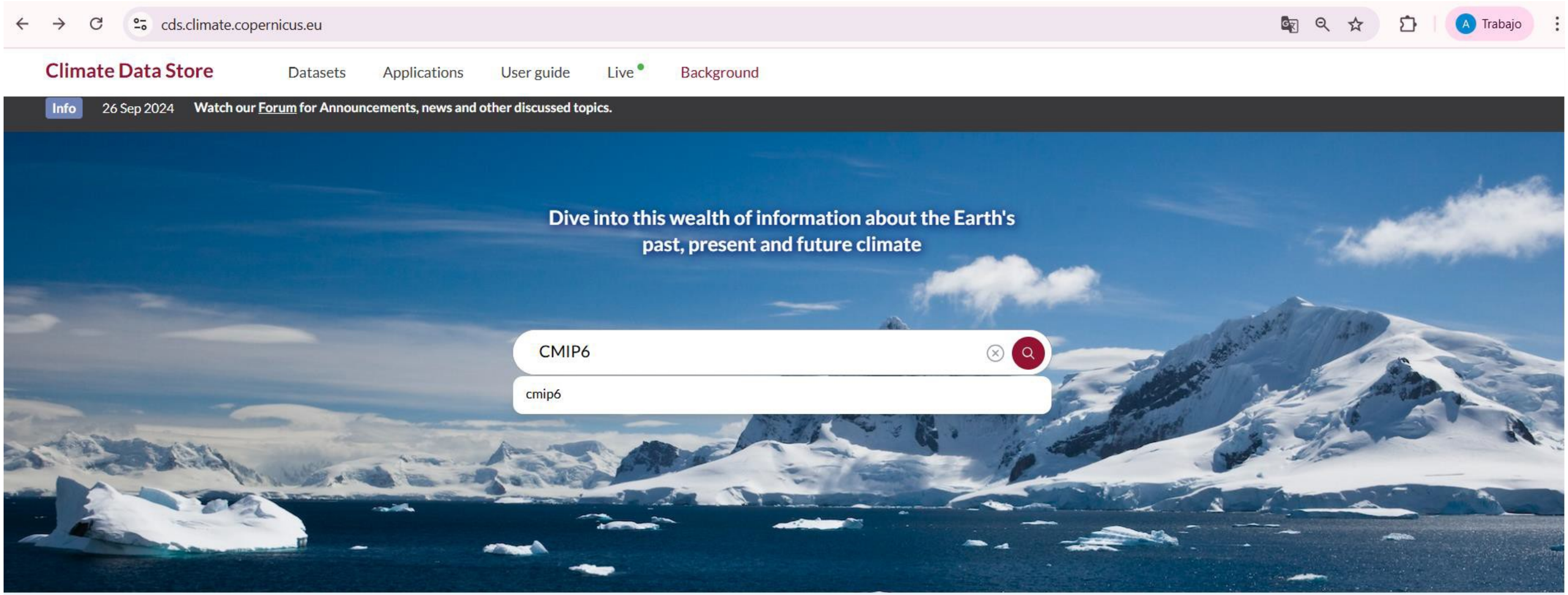
bash wget*.sh -s

-s skips security

```
/downloads/historical_download/CMCC-CM2-VHR4]> bash wget_script_2025-1-30_0-22-33.sh -s
```

```
********************************************************************************
*                                                                              *
* Note that new functionality to allow authentication without the need for     *
* certificates is available with this version of the wget script.  To enable,  *
* use the "-H" option and enter your OpenID and password when prompted:        *
*                                                                              *
* $ wget_script_2025-1-30_0-22-33.sh -H [options...]                           *
*                                                                              *
* For a full description of the available options use the help option:        *
*                                                                              *
* $ wget_script_2025-1-30_0-22-33.sh -h                                        *
*                                                                              *
********************************************************************************
Running wget_script_2025-1-30_0-22-33.sh version: 1.3.2
Use wget_script_2025-1-30_0-22-33.sh -h for help.

Script created for 65 file(s)
(The count won't match if you manually edit this file!)



pr_day_CMCC-CM2-VHR4_hist-1950_r1i1p1f1_gn_19500101-19501231.nc ...Downloading
--2025-07-06 19:08:03--  https://esgf.ceda.ac.uk/thredds/fileServer/esg_cmip6/CMIP6/HighResMIP/CMCC/CMCC-CM2-VHR4/hist-1950/r1i1p1f1/day/pr/gn/v20210308/pr_day_CMCC-CM2-VHR4_hist-1950_r1i1p1f1_gn_19500101
-19501231.nc
Resolving esgf.ceda.ac.uk (esgf.ceda.ac.uk)... 130.246.128.97
Connecting to esgf.ceda.ac.uk (esgf.ceda.ac.uk)|130.246.128.97|:443... connected.
HTTP request sent, awaiting response... 206 Partial Content
Length: 1012955932 (966M), 1003302808 (957M) remaining [application/octet-stream]
Saving to: 'pr_day_CMCC-CM2-VHR4_hist-1950_r1i1p1f1_gn_19500101-19501231.nc'

01-19501231.nc                     5%[+===>                                     ]  49.12M  2.46MB/s    eta 6m 20s
```

Climate Data Store - CDS



https://cds.climate.copernicus.eu/

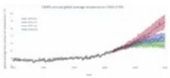
CDS - CMIP6

cds.climate.copernicus.eu/datasets?q=CMIP6

Climate Data Store | Datasets | Applications | User guide | Live | Background

We found 13 results | 0 on ADS | 0 on EWDS

Filter by
- Product type
- Provider
- Sector
- Spatial coverage
- Temporal coverage
- Variable domain

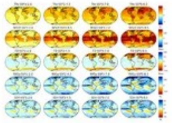


CMIP6 climate projections

Updated on 10 January 2025

This catalogue entry provides daily and monthly global climate projections data from a large number of experiments, models and tim
the sixth phase of the Coupled Model Intercomparison Project (CMIP6). CMIP6 data underpins the Intergovernmental Panel on Clin

✓ Quality Assurance | Climate projections | Global | Future | Past | Present | Atmosphere (surface) | Atmosphere (

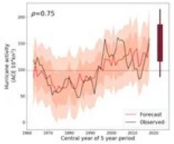


Climate extreme indices and heat stress indicators derived from CMIP6 global climate projections

Updated on 31 January 2025

The dataset provides climate extreme indices related to temperature and precipitation as defined by the Expert Team on Climate Ch
well as selected heat stress indicators (HSI). The indices are provided for historical and future climate projections (SSP1-2.6, SS...

Climate indices | Climate projections | Global | Future | Past | Land (biosphere)



CMIP6 predictions underpinning the C3S decadal prediction prototypes

Published on 23 March 2021

This catalogue entry provides daily and monthly global climate model data from Decadal Climate Predictions Project (DCPP) experir
Coupled Model Intercomparison Project (CMIP6). The decadal data in the Climate Data Store (CDS) are a quality-controlled subset c

Climate projections | Global | Future | Past | Present | Atmosphere (surface) | Atmosphere (upper air)

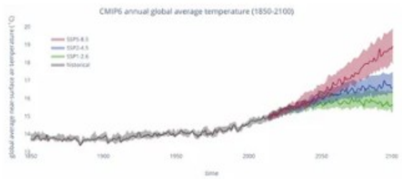
Funded by the European Union
Grant Agreement 101159497

CDS - Overview

CMIP6 climate projections

Overview | Download | Quality | Documentation

This catalogue entry provides daily and monthly global climate projections data from a large number of experiments, models and time periods computed in the framework of the sixth phase of the Coupled Model Intercomparison Project (CMIP6).



CMIP6 data underpins the Intergovernmental Panel on Climate Change 6th Assessment Report. The use of these data is mostly aimed at:

- addressing outstanding scientific questions that arose as part of the IPCC reporting process;
- improving the understanding of the climate system;
- providing estimates of future climate change and related uncertainties;
- providing input data for the adaptation to the climate change;
- examining climate predictability and exploring the ability of models to predict climate on decadal time scales;
- evaluating how realistic the different models are in simulating the recent past.

The term "experiments" refers to the three main categories of CMIP6 simulations:

- Historical experiments which cover the period where modern climate observations exist. These experiments show how the GCMs performs for the past climate and can be used as a reference period for comparison with scenario runs for the future. The period covered is typically 1850-2014

Quality Assurance

Data Management

Data records

Metadata

Documentation

References

Citation and attribution

DOI: 10.24381/cds.c866074c

Licence

CMIP6 - Data Access - Terms of Use

Publication date

2021-03-23

https://cds.climate.copernicus.eu/datasets/projections-cmip6?tab=overview

CDS - Quality tab

Datasets Applications User guide Live Background

CMIP6 climate projections

Overview | Download | Quality | Documentation

The Quality information is work in progress, and the content for this release was prepared based on the previous operational version of the CDS. The CDS datasets are assessed by the Evaluation and Quality Control (EQC) function of C3S independently of the data supplier.

Fitness for purpose

Evaluated on 20/03/2025

The CMIP6 initiative brings together state-of-the-art Global Climate Models (GCMs) to enhance our understanding of past, present, and future climate dynamics driven by natural variability and changes in anthropogenic radiative forcing. GCMs are fully coupled, namely, they are idealised for reproducing the complex interactions among the different components of the climate system (atmosphere, sea, land, ice, sea-ice).

Key strengths

- **Global coverage**: GCMs produce self-consistent climate simulations over the entire Globe for a wide spectrum of variables belonging to the different climate system components (atmosphere, sea, land, ice). For the atmospheric variables, different pressure levels can be selected.
- **Temporal coverage**: CMIP6 provide climate integrations over long periods. This is essential to a proper evaluation of internal climate variability and the inherent statistical robustness of trends.
- **Multiple scenarios**: Future projections uncertainty can be covered by considering different hypotheses of future radiative forcing (SSPs). This informs about the dependency of future change trajectories on future societal paths (scenario uncertainty).
- **Multi-model ensemble**: The large number of GCMs present in CMIP6 allows to cover the uncertainty due to the model response to a given level of radiative forcing (model uncertainty).

Key limitations

- **Relatively coarse resolution**: GCMs are idealised to study the response of the large-scale circulation and teleconnections to changes in radiative forcing. Still, relatively coarse resolution (from 80 km to 250 km) hinders the possibility of directly connecting their outputs to regional/local scale impact studies like hydrology, agriculture, tourism and energy sectors. For instance, if the user question is whether an alpine valley can be favourable for wind power installation under future climate conditions, GCMs may be a sub-optimal tool for this type of analysis.

Quality Assurance

- Data Management
- Data records
- Metadata
- Documentation

References

Citation and attribution

DOI: 10.24381/cds.c866074c

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Publication date

2021-03-23

Update date

2025-01-10

Standard metadata

STAC

CDS - Download

Climate Data Store | Datasets | Applications | User guide | Live | Background

CMIP6 climate projections

Overview | Download | Quality | Documentation

Complete all required fields before submitting the request.

Temporal resolution

At least one selection must be made

- Monthly
- Daily
- Fixed (no temporal resolution)

Experiment

At least one selection must be made

- Historical
- SSP1-1.9
- SSP1-2.6
- SSP4-3.4
- SSP5-3.4OS
- SSP2-4.5
- SSP4-6.0
- SSP3-7.0
- SSP5-8.5

Variable

At least one selection must be made

- Air temperature
- Capacity of soil to store water
- Daily maximum near-surface air temperature
- Daily minimum near-surface air temperature
- Eastward near-surface wind
- Eastward wind
- Evaporation including sublimation and transpiration
- Geopotential height
- Grid-cell area for atmospheric grid variables
- Grid-cell area for ocean variables

Quality Assurance

- Data Management
- Data records
- Metadata
- Documentation

References

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Publication date

2021-03-23

Update date

CDS - Download

Model Clear all

- ACCESS-CM2 (Australia)
- AWI-CM-1-1-MR (Germany)
- BCC-CSM2-MR (China)
- CAMS-CSM1-0 (China)
- CanESM5-CanOE (Canada)
- CESM2-FV2 (USA)
- CESM2-WACCM-FV2 (USA)
- CMCC-CM2-HR4 (Italy)
- ACCESS-ESM1-5 (Austra
- AWI-ESM-1-1-LR (Germa
- BCC-ESM1 (China)
- CanESM5 (Canada)
- CESM2 (USA)
- CESM2-WACCM (USA)
- CIESM (China)
- CMCC-CM2-SR5 (Italy)

Year Select all Clear all

1850-1899

1900-1949

1950-1999

2000-2049

Clear all

2000	2001	2002	2003	2004
2005	2006	2007	2008	2009
2010	2011	2012	2013	2014
2015	2016	2017	2018	2019
2020	2021	2022	2023	2024
2025	2026	2027	2028	2029

CDS - Download

API request

Please go to the documentation page for information as to how to use the CDS API.

Hide API request code

```
import cdsapi

dataset = "projections-cmip6"
request = {
    "temporal_resolution": "daily",
    "experiment": "ssp5_8_5",
    "variable": "daily_maximum_near_surface_air_temperature",
    "model": "access_cm2",
    "year": [
        "2015", "2016", "2017",
        "2018", "2019", "2020",
        "2021", "2022", "2023",
        "2024", "2025", "2026",
        "2027", "2028", "2029",
        "2030", "2031", "2032",
        "2033", "2034", "2035",
        "2036", "2037", "2038",
        "2039", "2040", "2041",
        "2042", "2043", "2044",
        "2045", "2046", "2047",
        "2048", "2049"
    ],
    "month": [
        "01", "02", "03",
        "04", "05", "06",
        "07", "08", "09",
        "10", "11", "12"
    ],
    "day": [
        "01", "02", "03",
        "04", "05", "06",
        "07", "08", "09",
        "10", "11", "12",
        "13", "14", "15",
        "16", "17", "18",
        "19", "20", "21",
```


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CDS and ESGF - Some differences

- In the **CDS**, some datasets include **fewer variables** and **ensemble members** than in ESGF; **daily data** is not available for every variable (e.g. soil moisture)
- In the **CDS**, users can **select a specific region** and **period of interest** before downloading
- CDS currently includes **fewer CMIP activities** compared to the **ESGF**
- CDS also provides **specific, tailored products** developed for community use (e.g. Climate extreme indices and heat stress indicators derived from CMIP6 global climate projections)
- Some datasets in the CDS include a **Quality tab** with information on **fitness for purpose, Quality assurance** and **Quality assessment** details

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Inspection of climate model outputs

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cmcc Centro Euro-Mediterraneo sui Cambiamenti Climatici
JUSTUS-LIEBIG-UNIVERSITAT GIESSEN
Universiteit Antwerpen
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Interactive break - Sharing our programming background

- ❑ Which **programming languages** are you comfortable with? (e.g. Python, R, Fortran, MATLAB...)
- ❑ Do you work with **NetCDF files**?
- ❑ Have you used tools like **ncview** to quickly visualise data?
- ❑ Are you familiar with platforms like the **ESGF** or the **Copernicus Climate Data Store (CDS)**?
- ❑ Do you use **CDO** (Climate Data Operators) for data processing?
- ❑ Do you work in **JupyterLab** or similar notebook environments?
- ❑ Are you familiar with **bash**? Do you use it for scripting or running workflows?

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Grant Agreement 101159497

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