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METEO FRANCE
À VOS CÔTÉS, DANS UN CLIMAT QUI CHANGE

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PEPR TRACCS

Transformer la modélisation du climat pour les services climatiques

1. What is at stake with climate modelling ?

Julie Deshayes, CNRS IPSL
et V. Balaji, Schmidt Futures

"Europe is building a 'digital twin' of Earth to revolutionize climate forecasts"
Science, Oct 1, 2020

2021 : Syukuro Manabe reçoit
le prix Nobel de physique

PNAS PERSPECTIVE OPEN ACCESS

Are general circulation models obsolete?

V. Balaji[a,b,1], Fleur Couvreux[c], Julie Deshayes[d], Jacques Gautrais[e], Frédéric Hourdin[f], and Catherine Rio[c]

Edited by Andrew Gettelman, National Center for Atmospheric Research; received April 1, 2022; accepted September 9, 2022 by Editorial Board Member Akkihebbal R. Ravishankara

Traditional general circulation models, or GCMs—that is, three-dimensional dynamical models with unresolved terms represented in equations with tunable parameters—have been a mainstay of climate research for several decades, and some of the pioneering studies have recently been recognized by a Nobel prize in Physics. Yet, there is considerable debate around their continuing role in the future. Frequently mentioned as limitations of GCMs are the structural error and uncertainty across models with different representations of unresolved scales and the fact that the models are tuned to reproduce certain aspects of the observed Earth. We consider these shortcomings in the context of a future generation of models that may address these issues through substantially higher resolution and detail, or through the use of machine learning techniques to match them better to observations, theory, and process models. It is our contention that calibration, far from being a weakness of models, is an essential element in the simulation of complex systems, and contributes to our understanding of their inner workings. Models can be calibrated to reveal both fine-scale detail and the global response to external perturbations. New methods enable us to articulate and improve the connections between the different levels of abstract representation of climate processes, and our understanding resides in an entire hierarchy of models where GCMs will continue to play a central role for the foreseeable future.

climate modeling | machine learning | model calibration | model hierarchy

The general circulation model, or GCM, is a mainstay of research into the evolving state of the Earth system over a range of timescales. The term dates back to the very origin of numerical simulation of the atmosphere (e.g., refs. 1 and 2). The equations governing the general circulation of fluids on a spinning sphere use the basic Navier–Stokes equations, whose form specialized for the planetary circulation was first formulated at the turn of the 20th century (e.g., refs. 3 and 4). However, closed-form solutions are not readily available, and their use as research and prediction tools had to await the advent of numerical solution in the 1950s (5).

The 2021 Nobel prizes in Physics honor some of the work done with GCMs. The first formal global warning of anthropogenic climate change, the Charney Report (6), was substantially based on the pioneering work of Syukuro Manabe, who confirmed 19th century speculations on the warming effect of adding CO_2. While normally attributed to Tyndall and Arrhenius, the earlier work of Eunice Foote has recently come to light (7). She, in fact, presciently remarked, "An atmosphere of that gas would give to our earth a high temperature" (8). While Foote and others were talking principally about the radiative effects of CO_2, it was Manabe and others who included dynamical considerations, the transport of heat vertically through convection (9), as well as from the equator poleward through atmospheric and oceanic circulation (e.g., ref. 10). Besides, GCMs also play a central role in the work of another of the 2021 winners, Klaus Hasselmann, who laid the groundwork for the statistical methods behind the field of detection and attribution of climate change (e.g., ref. 11). The detection of climate change requires extracting the signal of forced response in simulations from natural variability, and the attribution of it to external climate forcing agents, such as CO_2 emissions, again requires counterfactual runs of a GCM where that particular forcing is absent.

It may seem an odd juncture, when a Nobel prize has just been awarded for GCM-based work, to speculate on the obsolescence of the GCM. However, there has been a considerable body of literature, for a while, arguing that the limitations of GCMs require a major overhaul for further progress in climate modeling. It has been noted (see, e.g., ref. 12) that the bounds of uncertainty on equilibrium climate sensitivity (ECS: the asymptotic response of a model climate to a doubling of CO_2 concentration) has not significantly diminished since the Charney Report (6). Furthermore, a systematic synthesis of multiple lines of evidence to constrain ECS in ref. 13 indicates, in several places, a diminishing role for GCMs relative to other sources of information. Some have taken a leap from here to assert that the entire project of parameterization—the discovery of parsimonious representation through insight or mathematical methods—may have no future (e.g., refs. 14 and 15), and that large-scale computation is the way forward.

It is perhaps no accident that this debate takes place at a particular inflection point in the history of computing (16), where it is now possible to marshal and extract information from data at an unprecedented scale, the era of big data and machine learning (ML). These methods have led to some spectacular successes in various fields: AlphaFold, for

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¿General Circulation Models ?

ocean, atmosphere = geophysical fluids

- → mathematical equations
- → physical approximations
- → algorithms for spatio-temporal discretisation
- → computing programs or softwares
- → execution on HPC infrastructures
- → climate simulations !

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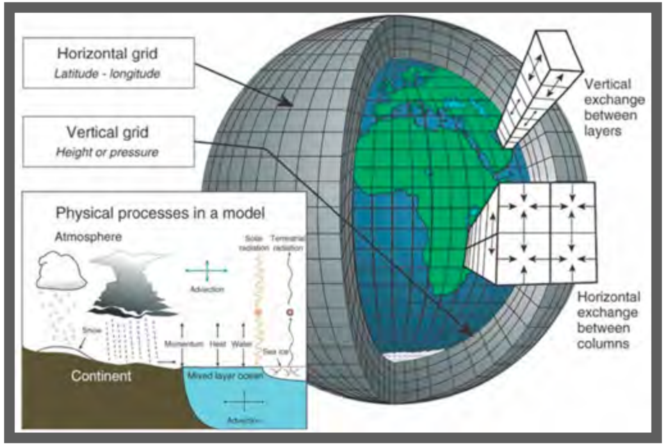
What ails the GCMs ?

- The column abstraction vs large-scale organization

- calibration or tuning of parameters

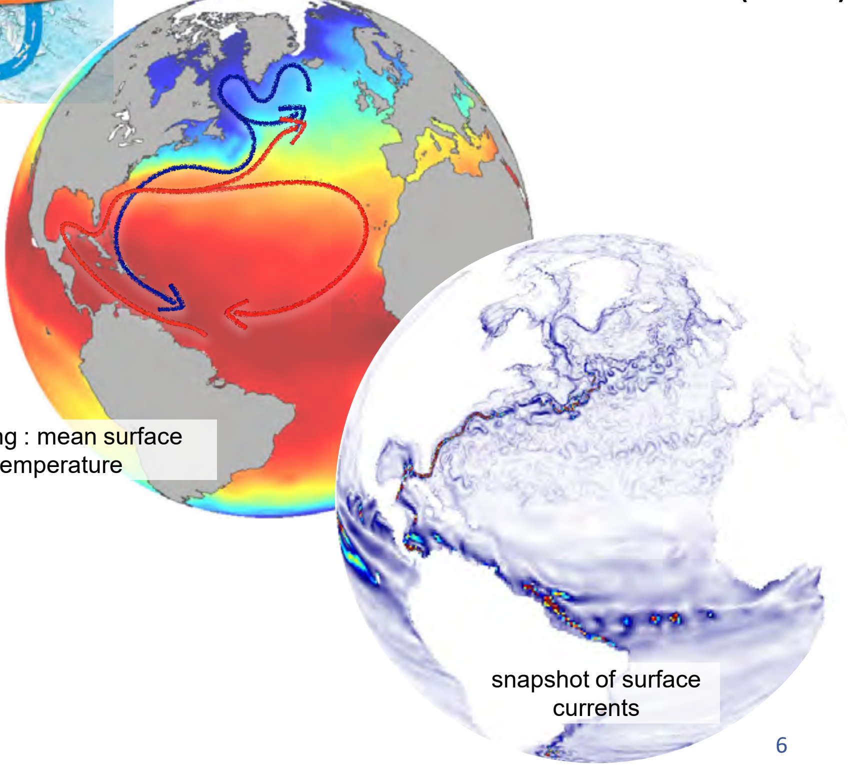
- GCMs are numerous :
  114 for CMIP6 feeding IPCC AR6



Take home messages after 50 years of climate modelling…

✓ Spatial resolution must derive from scientific question :

Meridional Overturning Circulation (MOC)



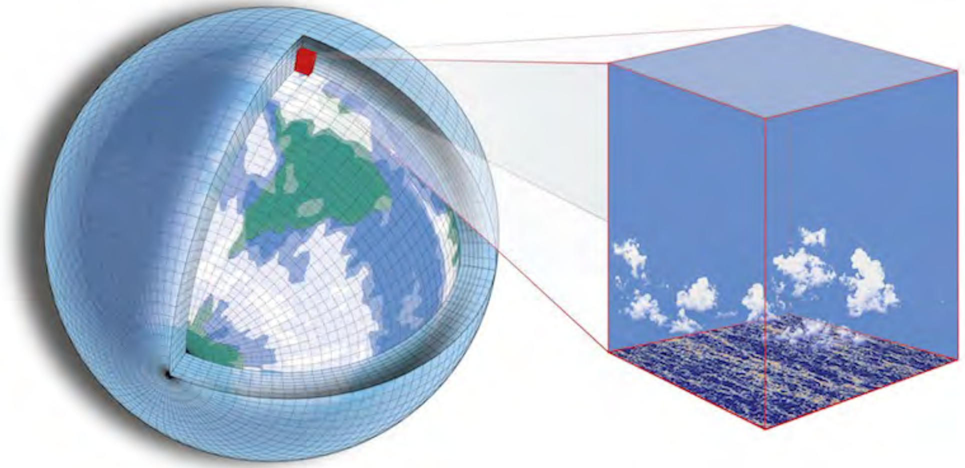
Take home messages after 50 years of climate modelling…

✓ Climate simulations contain various sources of uncertainties :

structural : related to mathematical choices and plysical approximations in build-up of models

parametric : related to processes that are not explicit represented

intrinsic to climate !



Take home messages after 50 years of climate modelling…

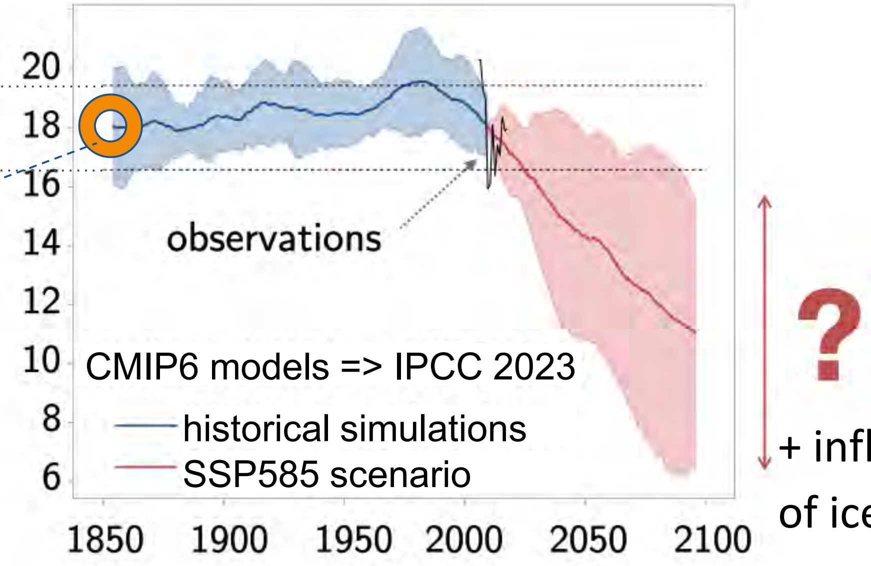
✓ Climate simulations contain various sources of uncertainties :

structural

parametric

intrinsic to climate !

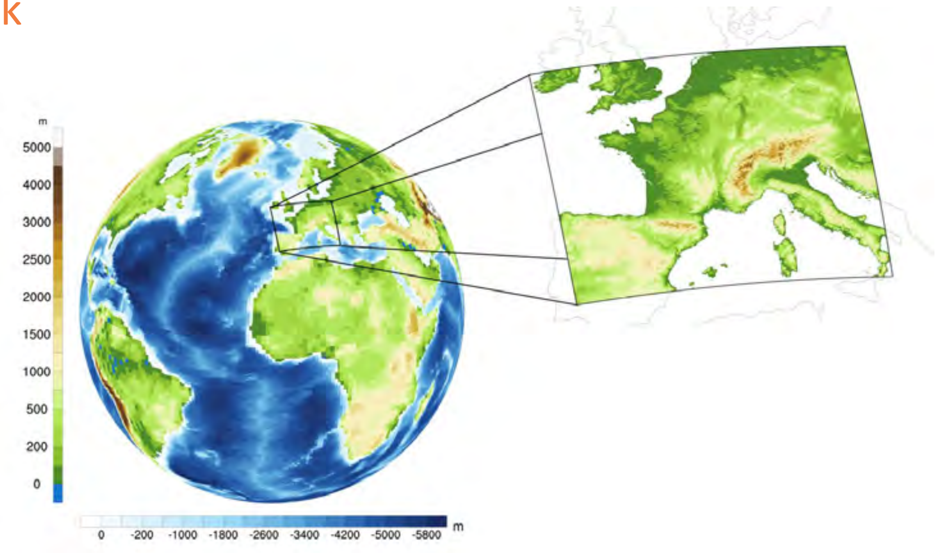
amplitude of the oceanic circulation MOC (Sv)
(adapted from Jackson et al. 2022 and Weijer et al. 2021)



+ influence of ice sheets !

What is at stake with climate services ?

- ❑ need for climate information at much smaller spatial scale (city, region…) with quantified uncertainties (risk assessment)

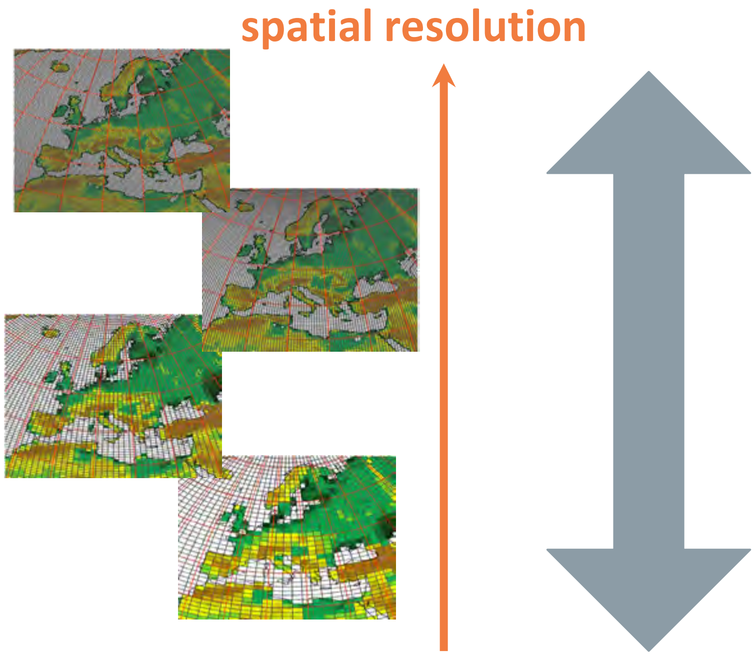


What is at stake with climate services ?

- ❑ need for climate information at much smaller spatial scale (city, region…) with quantified uncertainties (risk assessment)

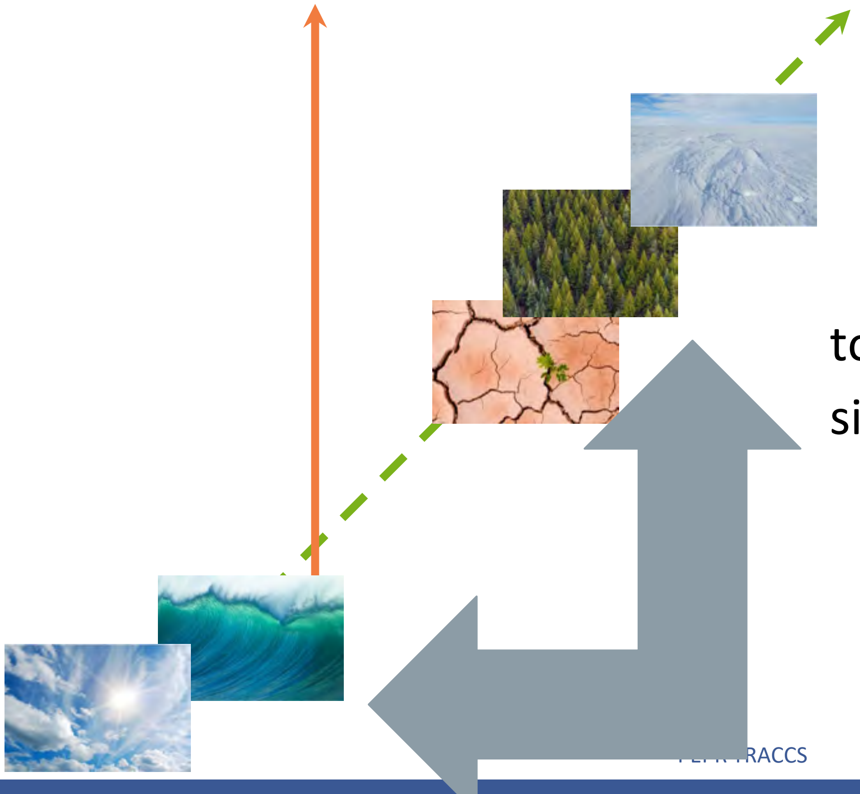
- ❑ multi-decadal projections with reduced uncertainties (to inform adaptation of infrastructures)

Proposition : assembling a hierarchy of models



to transfer climate information through different spatial scales

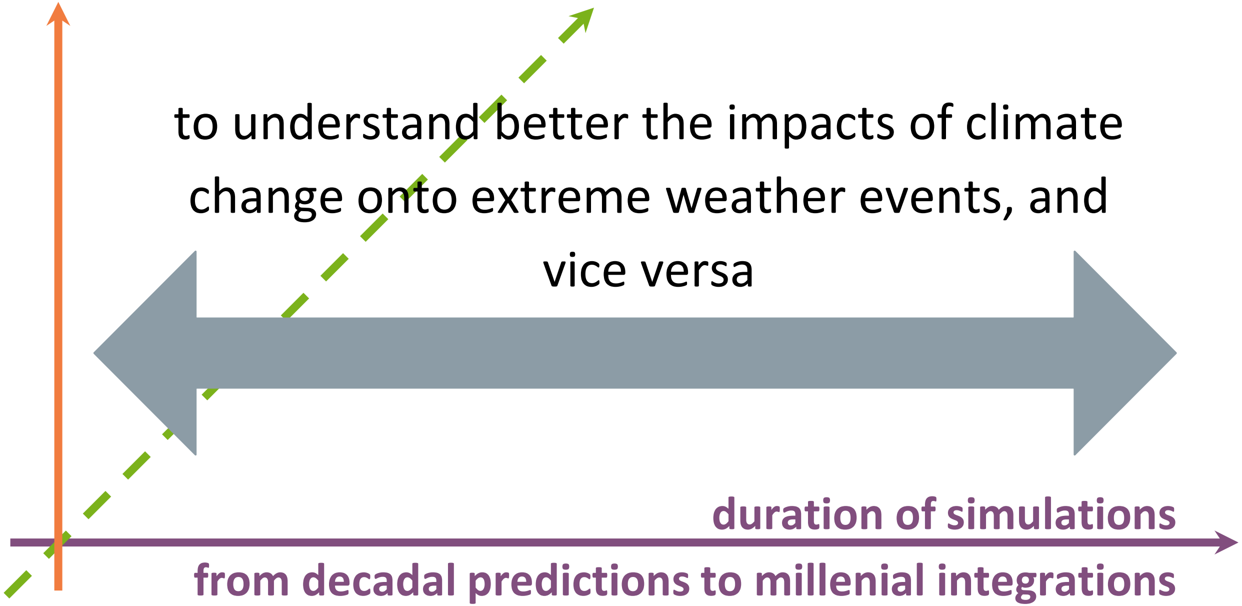
Proposition : assembling a hierarchy of models



complexity dimension: +/- ice sheets, BGC cycles …

to represent complex processes in simplified configurations

Proposition : assembling a hierarchy of models

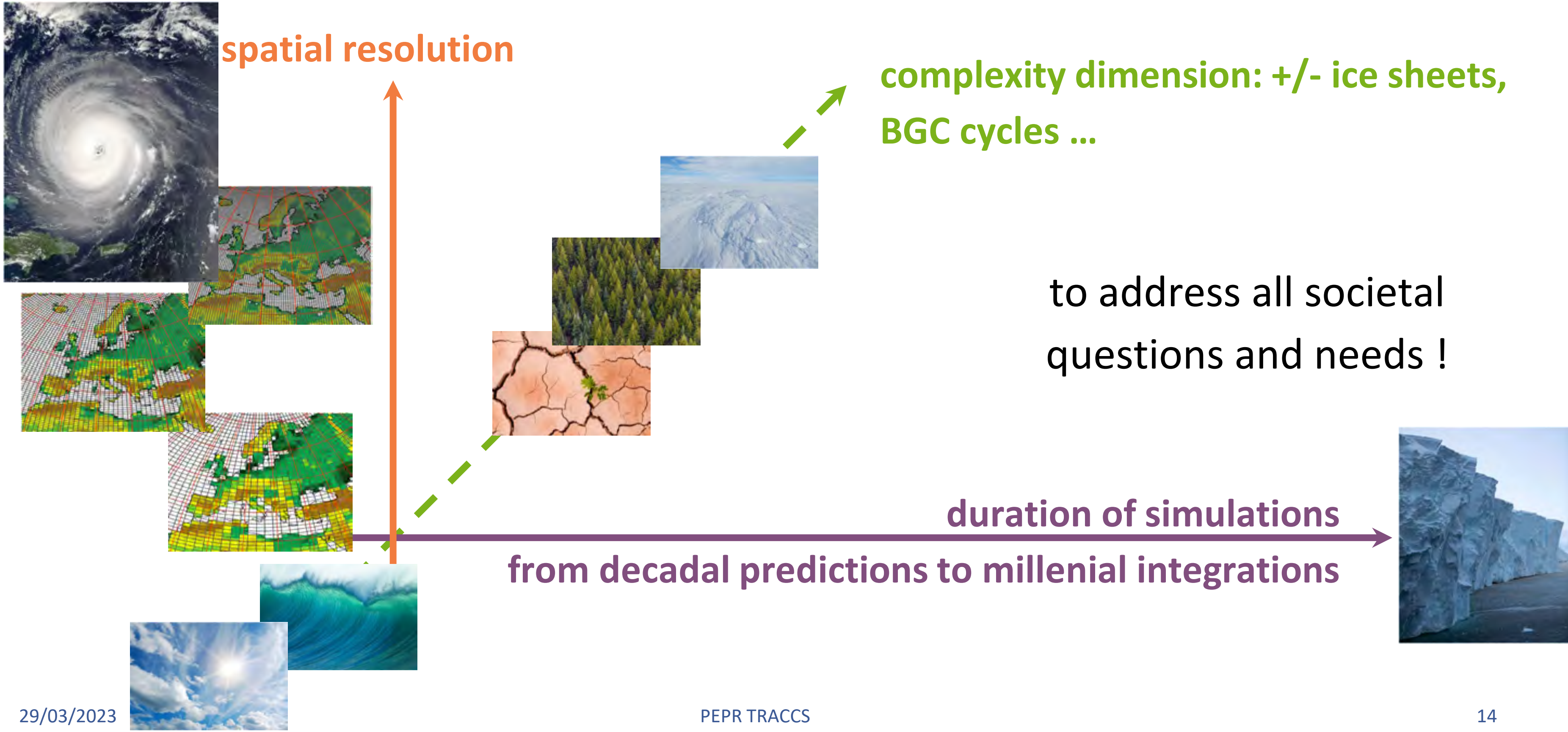


to understand better the impacts of climate change onto extreme weather events, and vice versa

duration of simulations

from decadal predictions to millenial integrations

Proposition : assembling a hierarchy of models



Challenge of computing infrastructures

- how to translate / adapt existing softwares, which are "alive", to new HPC infrastructures (without stopping development) ?

- which infrastructures are best adapted to climate simulations ?

→ strengthen links with AI to progress in data-model integration