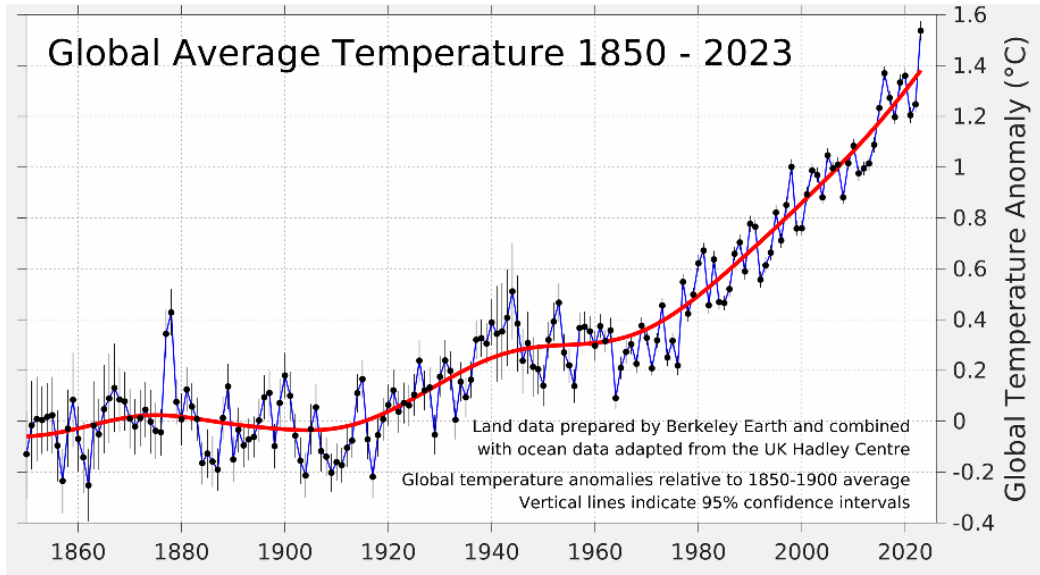


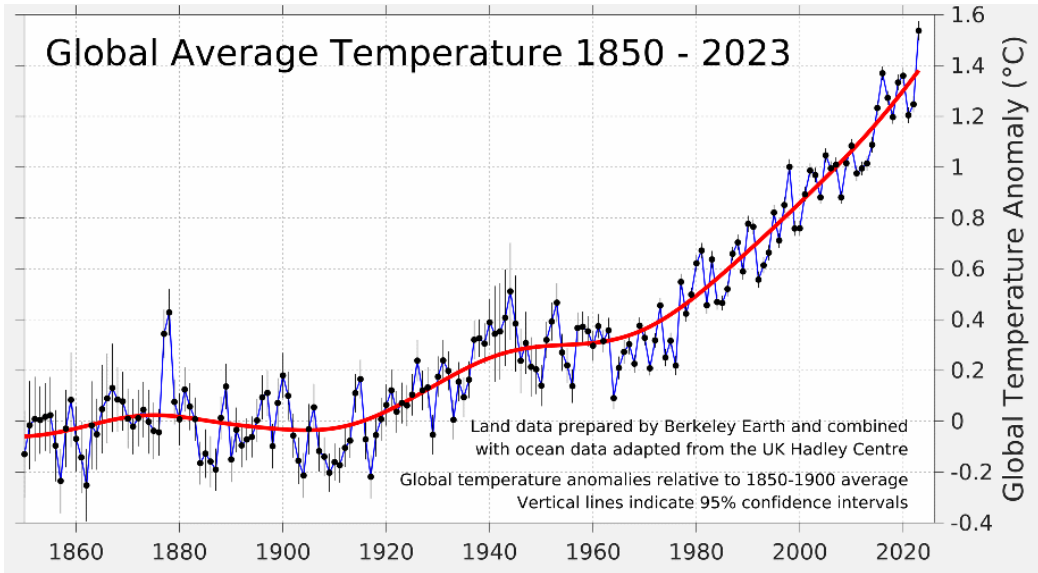
Predicting the weather
Predicting the Climate
some physics

Fabio D'Andrea
Laboratoire de Météorologie Dynamique - IPSL
Ecole Normale Supérieure, Paris
dandrea@lmd.ens.fr
01 44 32 22 31

Climate change is here:



Climate change is here:



Extreme climatic events

Rare, strong, damaging



Heat, Wind,
Rain

Climate change is here:

We are used to see the climate response to anthropogenic disturbance as an average response, notably the increase in global average temperature.

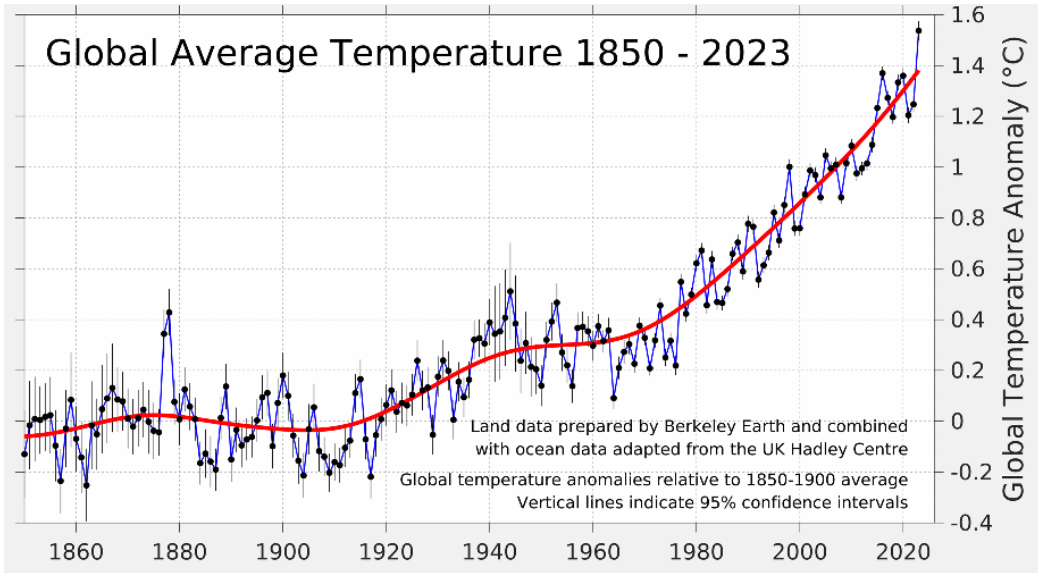
But climate change is above all the change in frequency and intensity of complex physical processes, storms, heatwaves, hurricanes, tornadoes, plankton blooms in the ocean, etc.

Extreme phenomena, due to their rarity and intensity, are those which cause the majority of impacts.

Heat, Wind,
Rain



Climate change is here:



Extreme climatic events

Rare, strong, damaging



Heat, Wind,
Rain

Predicting the weather
Predicting the Climate
some physics

Fabio D'Andrea
Laboratoire de Météorologie Dynamique - IPSL
Ecole Normale Supérieure, Paris
dandrea@lmd.ens.fr
01 44 32 22 31

Predicting the weather
Predicting the Climate
some physics

**SCIENTISTS CAN'T
EVEN PREDICT THE WEATHER
NEXT WEEK, WHY SHOULD I
BELIEVE WHAT THEY TELL US
ABOUT 100 YEARS
FROM NOW?**

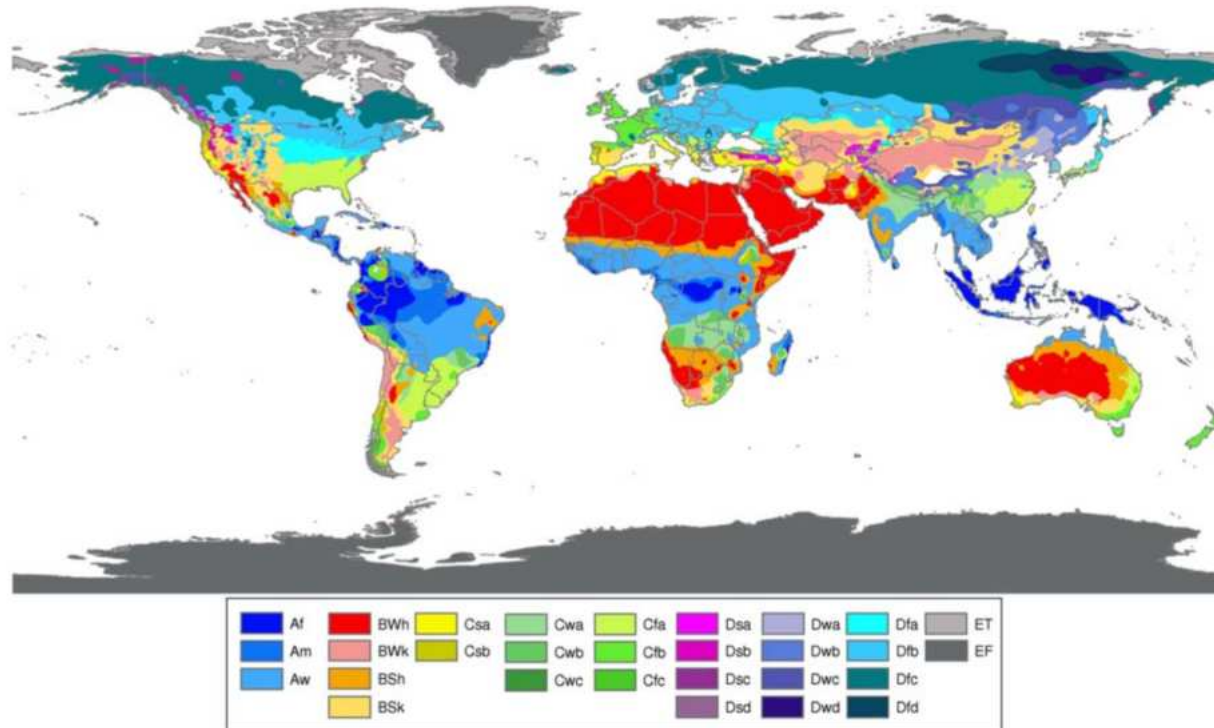


The study of climate was used to be a natural science, close to geography

Weather forecast was produced from observations and “synoptic” maps



1st	2nd	3rd	Description	Criteria*
A	f		Tropical - Rainforest	$T_{cold} \geq 18$ $P_{dry} \geq 60$
	m		- Monsoon	Not (Af) & $P_{dry} \geq 100 - MAP/2$
	w		- Savannah	Not (Af) & $P_{dry} < 100 - MAP/2$
B			Arid	$MAP < 10 \times P_{threshold}$
	W		- Desert	$MAP < 5 \times P_{threshold}$
	S		- Steppe	$MAP \geq 5 \times P_{threshold}$
C		h	- Hot	$MAT \geq 18$
		k	- Cold	$MAT < 18$
			Temperate	$T_{hot} > 10$ & $0 < T_{cold} < 18$
	s		- Dry Summer	$P_{dry} < 40$ & $P_{dry} < P_{wwet}/3$
	w		- Dry Winter	$P_{dry} < P_{swet}/10$
	f		- Without dry season	Not (Cs) or (Cw)
D		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a or b) & $1 \leq T_{mon10} < 4$
	s		- Dry Summer	$P_{dry} < 40$ & $P_{dry} < P_{wwet}/3$
	w		- Dry Winter	$P_{dry} < P_{swet}/10$
	f		- Without dry season	Not (Ds) or (Dw)
E		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a, b or d)
		d	- Very Cold Winter	Not (a or b) & $T_{cold} < -38$
	T		Polar - Tundra	$T_{hot} < 10$ $T_{hot} > 0$
F		- Frost	$T_{hot} \leq 0$	



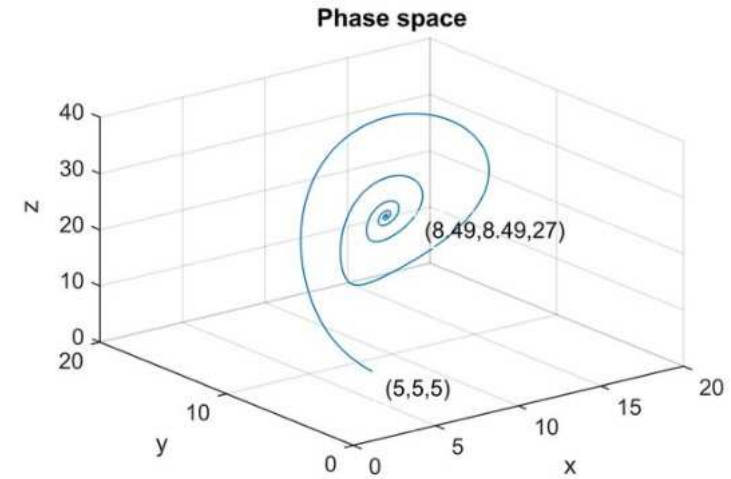
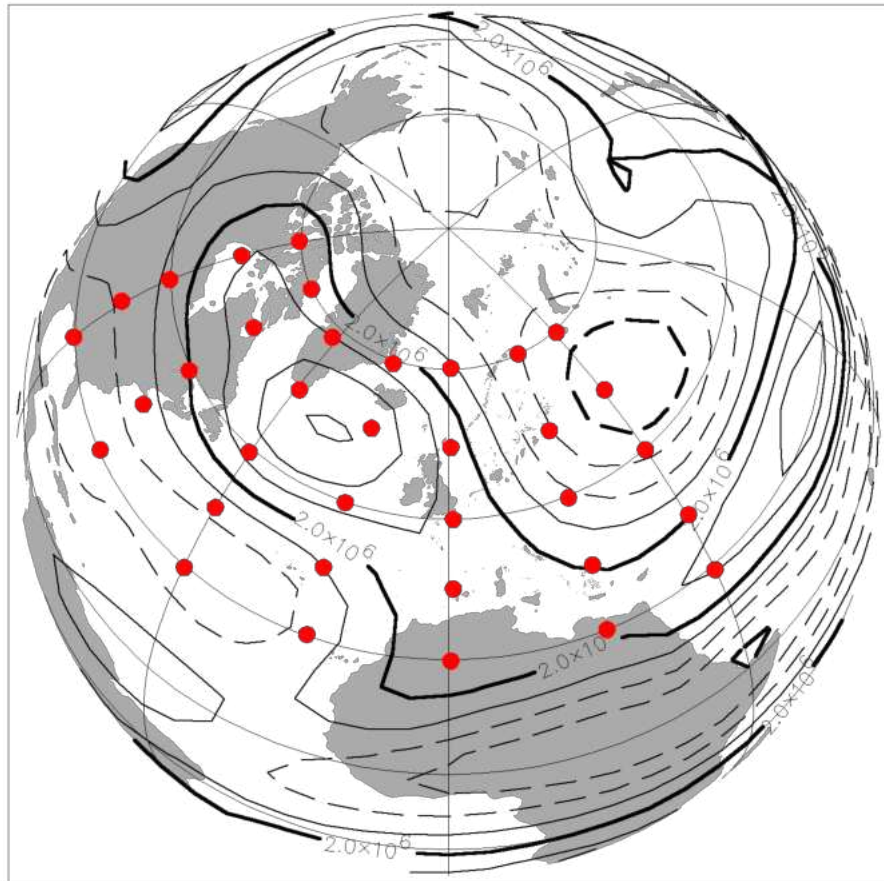
Köppen Classification (1900).

It was between the 1940s and 1950s that meteorology became a “hard science”. The weather is predicted using equations. In the 70s, a new revolution came about: the discovery of the chaotic nature of the atmosphere. What does “forecast” mean?



Climate is a dynamical system

$$\frac{\partial \mathbf{x}}{\partial t} = \mathbf{F}(\mathbf{x}; \mu)$$

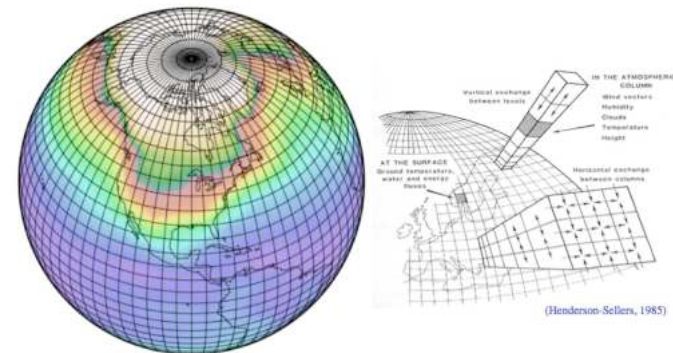


$$\mathbf{x} \in \mathbb{R}^N$$

How big is N??

Weather / Climate models: 10^{10-11}

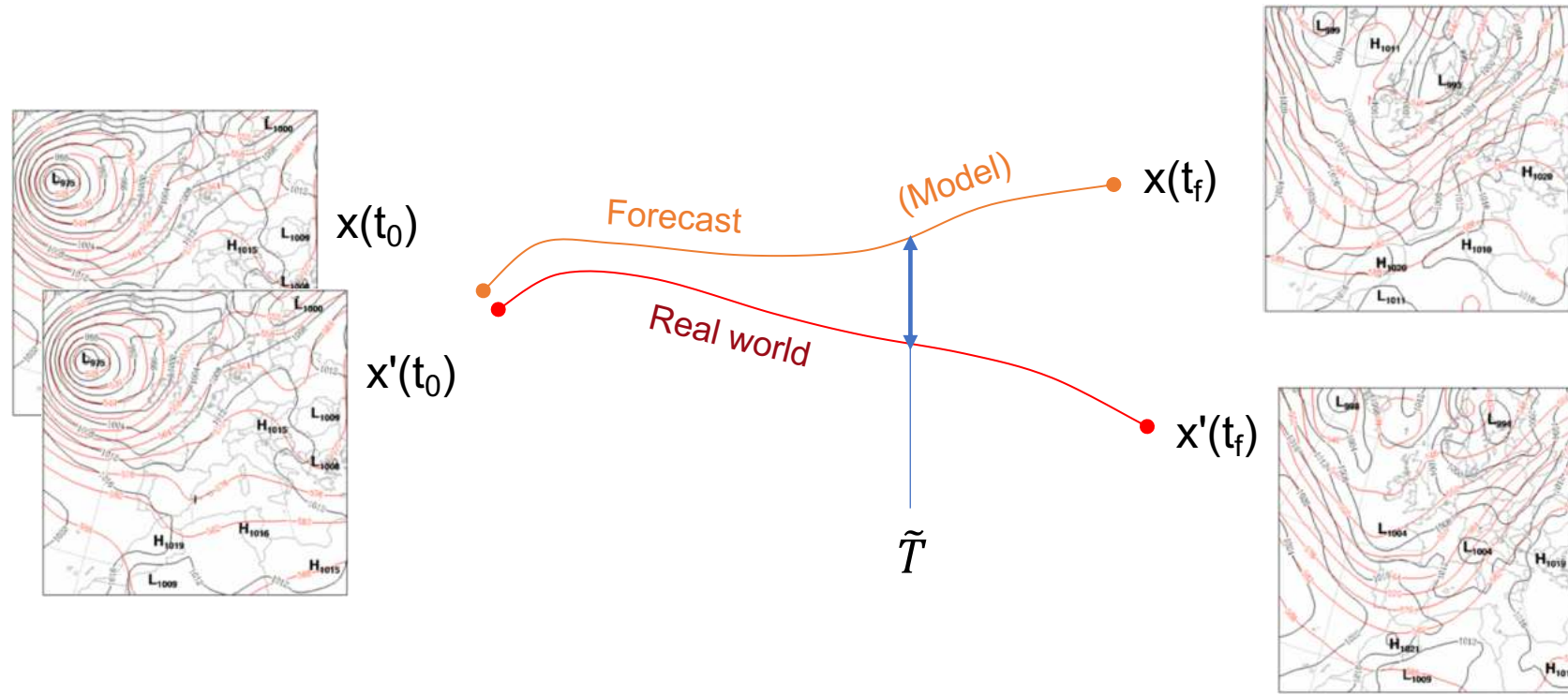
Atmosphere: 10^{45} !



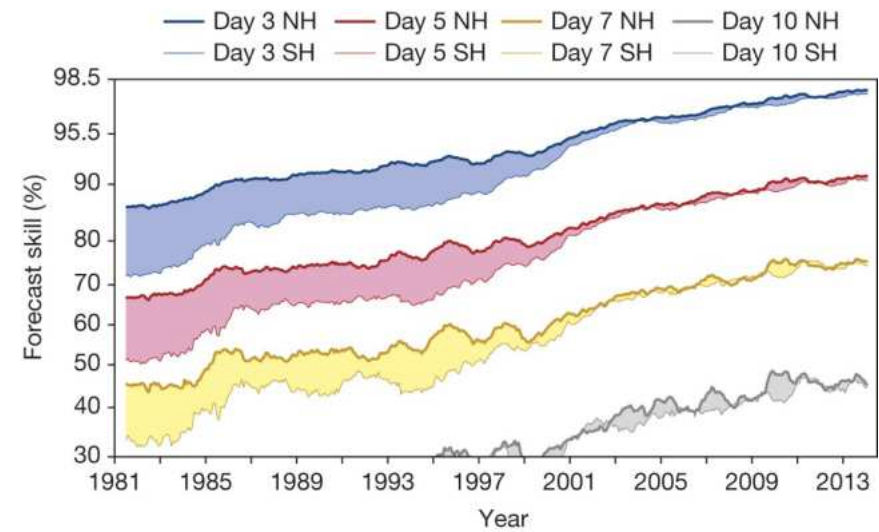
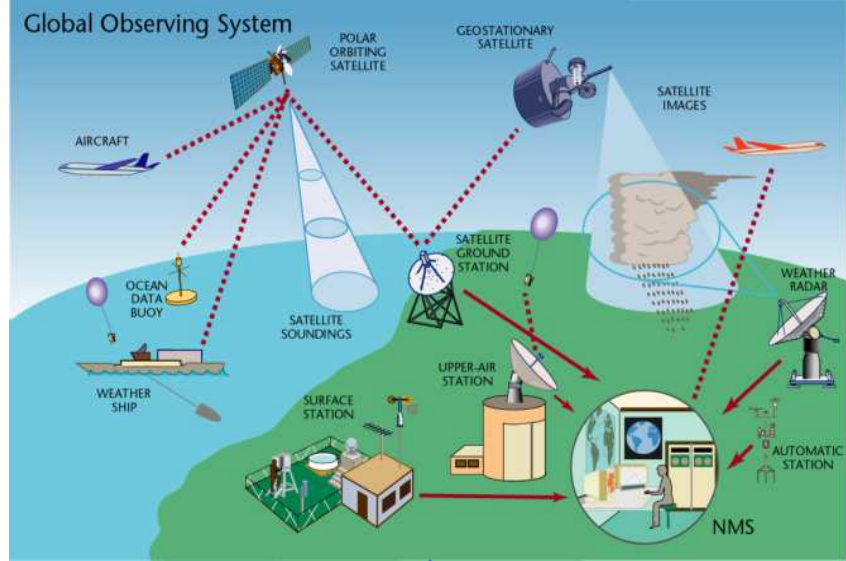
Weather forecast, climate forecast.

Weather forecasting is an initial conditions problem

Starting from an initial state of the atmosphere, we try to predict the values of a complete set of atmospheric variables, everywhere in space and in time. We seek the solution of a system of differential equations, given a condition at time zero.

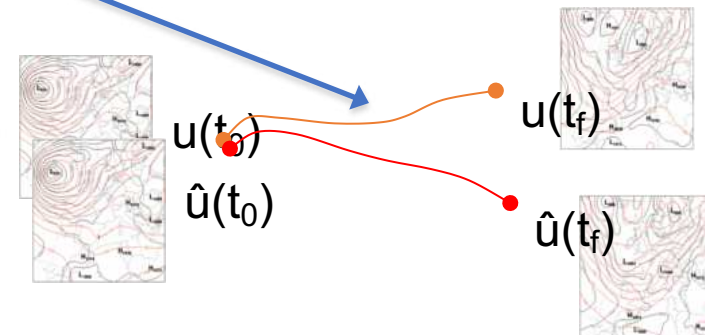
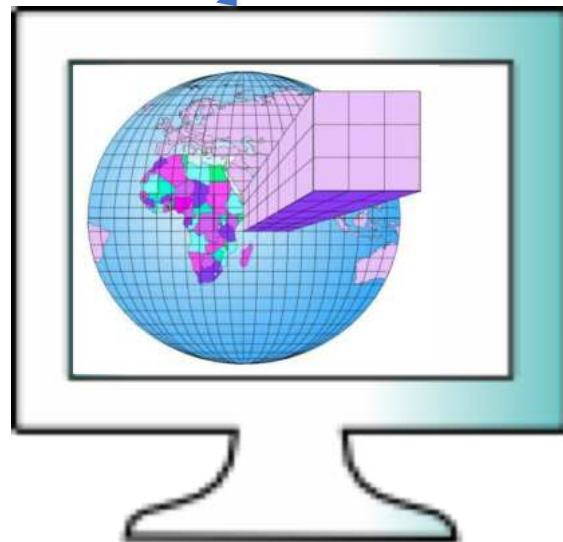


The main source of forecast error is poor knowledge of the initial state



Bauer et al. Nature 2016: “The quiet revolution of numerical weather prediction”

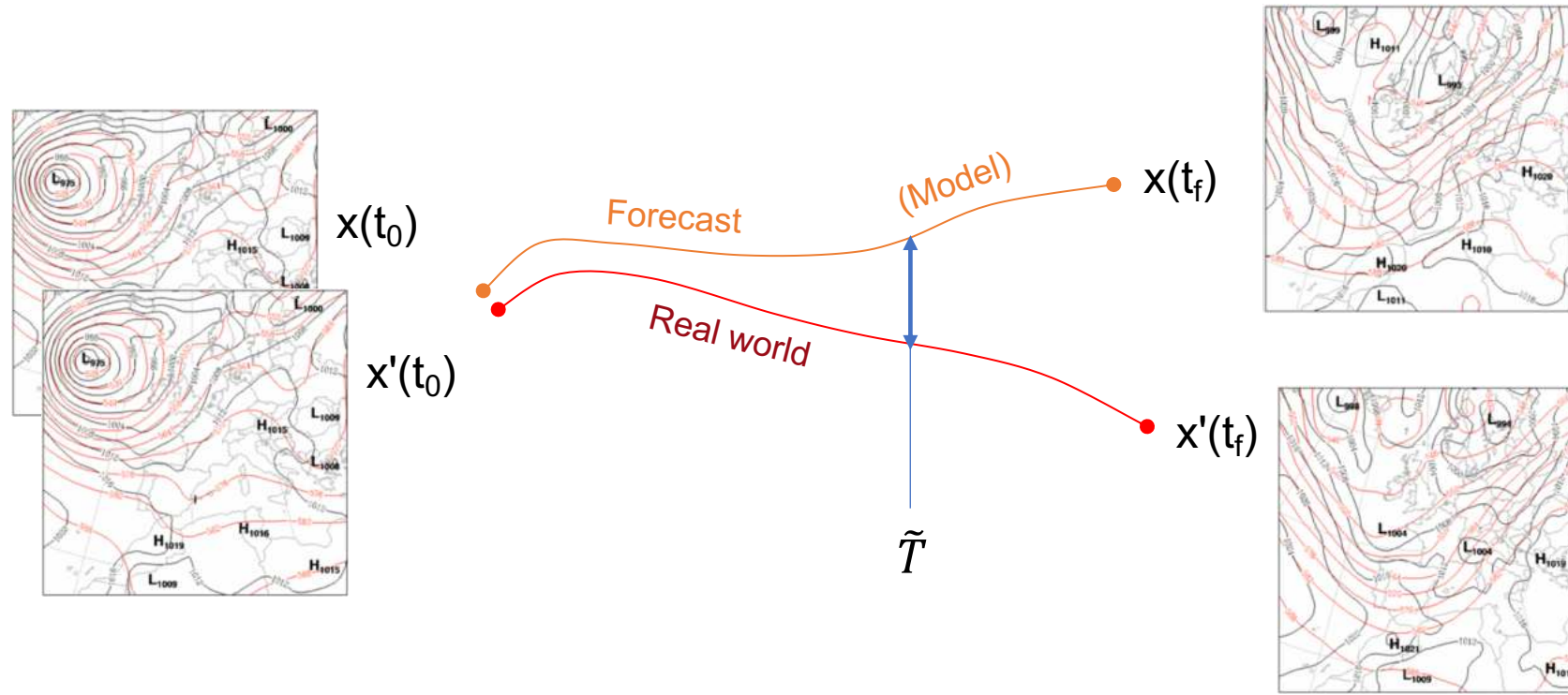
NWP chain



Weather forecast

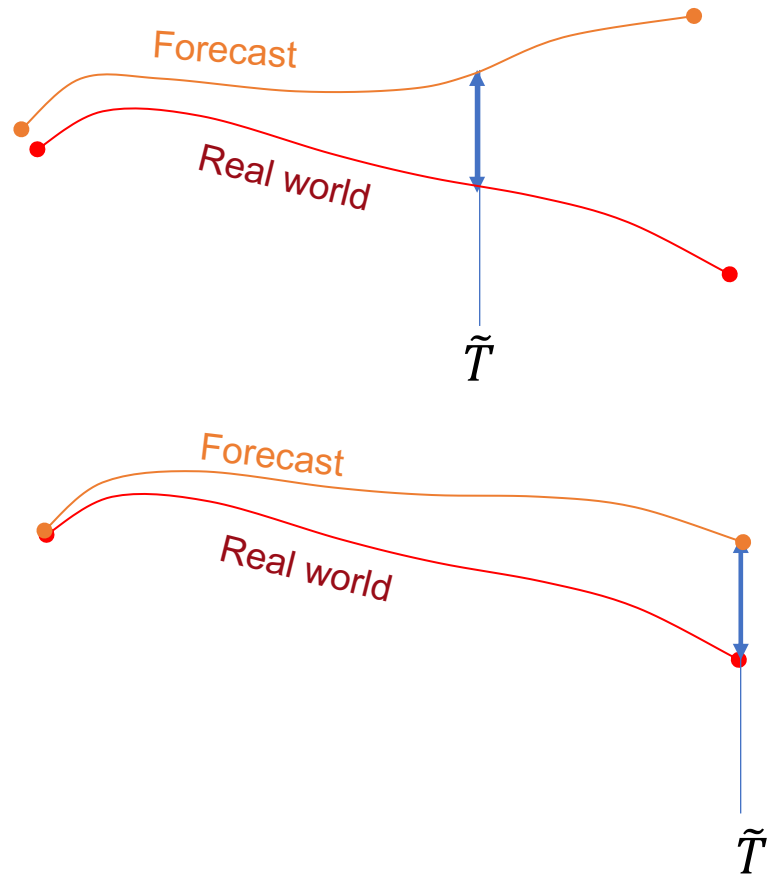
Weather forecasting is an initial conditions problem

Starting from an initial state of the atmosphere, we try to predict the values of a complete set of atmospheric variables, everywhere in space and in time. We seek the solution of a system of differential equations, given a condition at time zero.

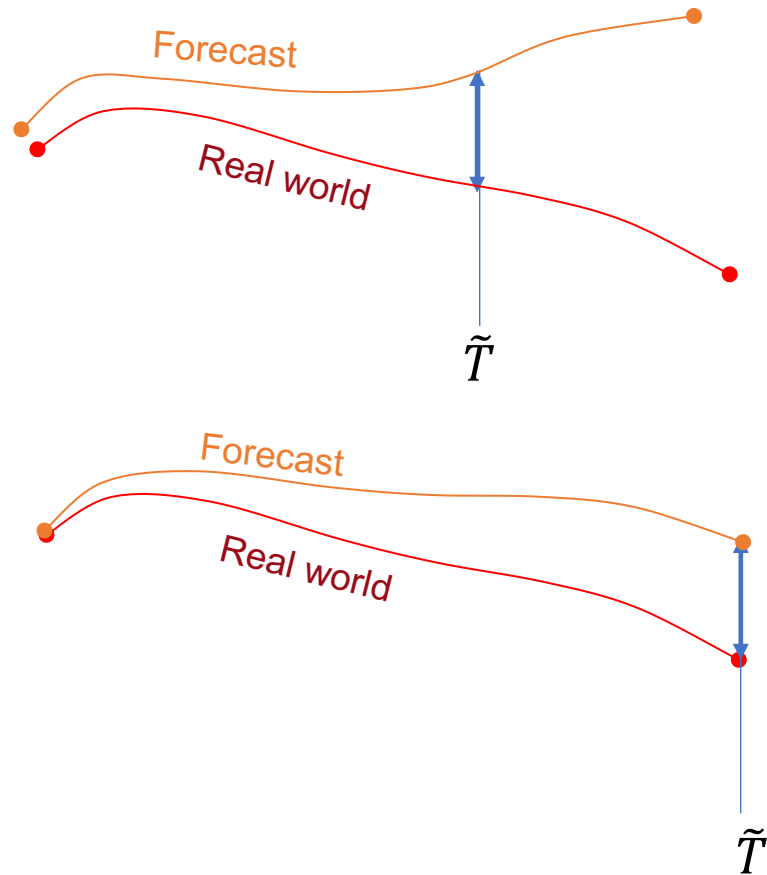


The main source of forecast error is poor knowledge of the initial state

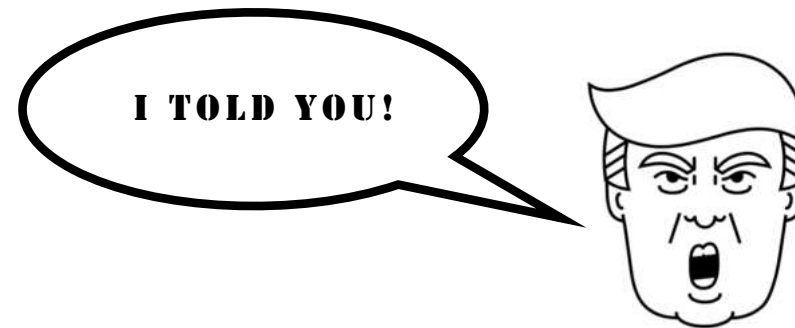
Can we make the initial error small enough to push the predictability limit as far off in the future as we want?



Can we make the initial error small enough to push the predictability limit as far off in the future as we want?



NO!

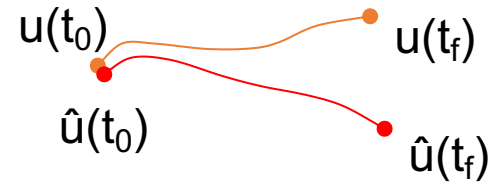




Henri Poincaré (1854–1912)

Some dynamical systems are so sensitive to a change of initial condition, that a small error has such an impact on their evolution that it is impossible to predict them

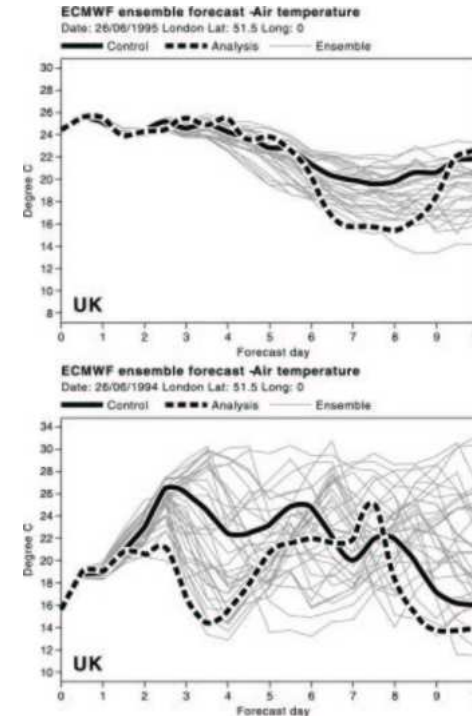
Deterministic Chaos.



Ed Lorenz (1917 – 2008)

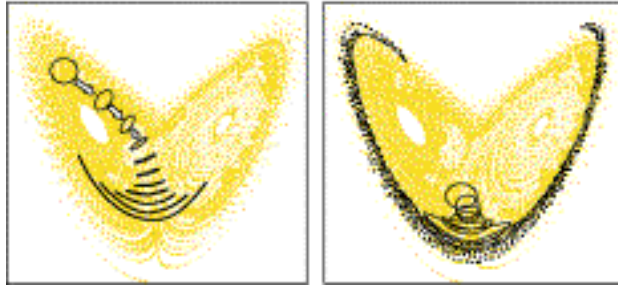
The atmosphere is one such system

The butterfly effect!

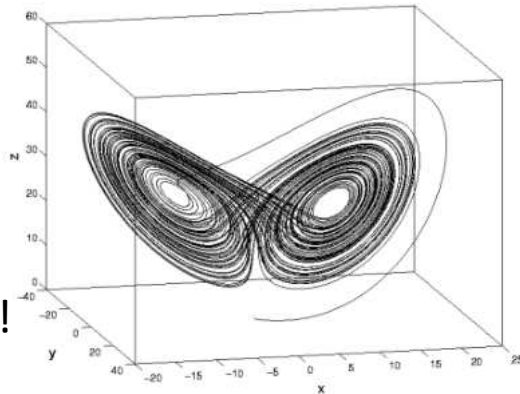




Ed Lorenz (1917 – 2008)



Credit: Tim Palmer



The butterfly effect!

Phase space

Deterministic Nonperiodic Flow¹

EDWARD N. LORENZ

Massachusetts Institute of Technology

(Manuscript received 18 November 1962, in revised form 7 January 1963)

ABSTRACT

Finite systems of deterministic ordinary nonlinear differential equations may be designed to represent forced dissipative hydrodynamic flow. Solutions of these equations can be identified with trajectories in phase space. For those systems with bounded solutions, it is found that nonperiodic solutions are ordinarily unstable with respect to small modifications, so that slightly differing initial states can evolve into considerably different states. Systems with bounded solutions are shown to possess bounded numerical solutions. A simple system representing cellular convection is solved numerically. All of the solutions are found to be unstable, and almost all of them are nonperiodic. The feasibility of very-long-range weather prediction is examined in the light of these results.

1. Introduction

Certain hydrodynamical systems exhibit steady-state flow patterns, while others oscillate in a regular periodic fashion. Still others vary in an irregular, seemingly haphazard manner, and, even when observed for long periods of time, do not appear to repeat their previous history.

These modes of behavior may all be observed in the familiar rotating-basin experiments, described by Fultz, et al. (1959) and Hide (1958). In these experiments, a cylindrical vessel containing water is rotated about its axis, and is heated near its rim and cooled near its center in a steady symmetrical fashion. Under certain conditions the resulting flow is as symmetric and steady as the heating which gives rise to it. Under different conditions a system of regularly spaced waves develops, and progresses at a uniform speed without changing its shape. Under still different conditions an irregular flow pattern forms, and moves and changes its shape in an irregular nonperiodic manner.

Lack of periodicity is very common in natural systems, and is one of the distinguishing features of turbulent flow. Because instantaneous turbulent flow patterns are so irregular, attention is often confined to the statistics of turbulence, which, in contrast to the details of turbulence, often behave in a regular well-organized manner. The short-range weather forecaster, however, is forced willy-nilly to predict the details of the large-scale turbulent eddies—the cyclones and anticyclones—which continually arrange themselves into new patterns.

Thus there are occasions when more than the statistics of irregular flow are of very real concern.

In this study we shall work with systems of deterministic equations which are idealizations of hydrodynamical systems. We shall be interested principally in nonperiodic solutions, i.e., solutions which never repeat their past history exactly, and where all approximate repetitions are of finite duration. Thus we shall be involved with the ultimate behavior of the solutions, as opposed to the transient behavior associated with arbitrary initial conditions.

A closed hydrodynamical system of finite mass may ostensibly be treated mathematically as a finite collection of molecules—usually a very large finite collection—in which case the governing laws are expressible as a finite set of ordinary differential equations. These equations are generally highly intractable, and the set of molecules is usually approximated by a continuous distribution of mass. The governing laws are then expressed as a set of partial differential equations, containing such quantities as velocity, density, and pressure as dependent variables.

It is sometimes possible to obtain particular solutions of these equations analytically, especially when the solutions are periodic or invariant with time, and, indeed, much work has been devoted to obtaining such solutions by one scheme or another. Ordinarily, however, nonperiodic solutions cannot readily be determined except by numerical procedures. Such procedures involve replacing the continuous variables by a new finite set of functions of time, which may perhaps be the values of the continuous variables at a chosen grid of points, or the coefficients in the expansions of these variables in series of orthogonal functions. The governing laws then become a finite set of ordinary differential

¹ The research reported in this work has been sponsored by the Geophysics Research Directorate of the Air Force Cambridge Research Center, under Contract No. AF 19(604)-4909.

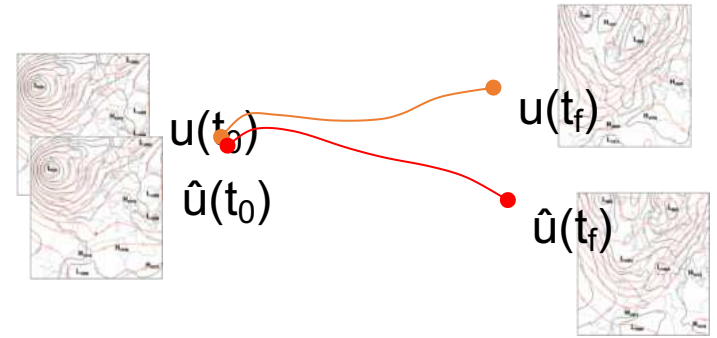
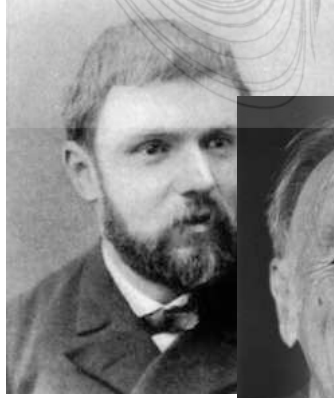


Une intelligence Qui, pour un instant donné, connaîtrait toutes les forces dont la nature est animée et la situation respective des êtres qui la composent, si d'ailleurs elle était assez vaste pour soumettre ces données à l'analyse, embrasserait dans la même formule les mouvements des plus grands corps de l'univers et ceux du plus léger atome : rien ne serait incertain pour elle, et l'avenir, comme le passé, serait présent à ses yeux.



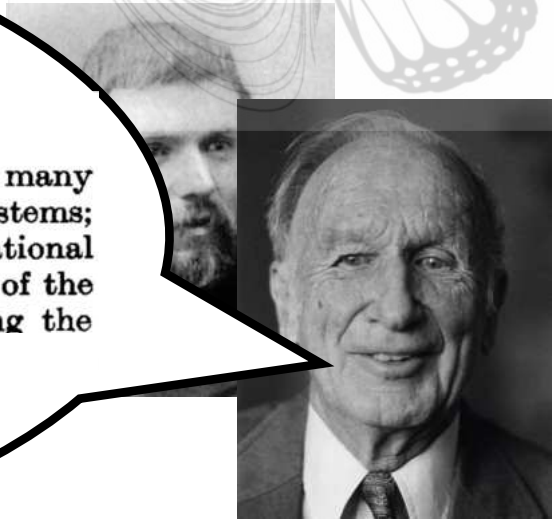
Pierre-Simon Laplace, « Essai philosophique sur les probabilités » (1819)

«The last nail on the grave of determinism» (?)





«The last nail on the grave of determinism» (?)

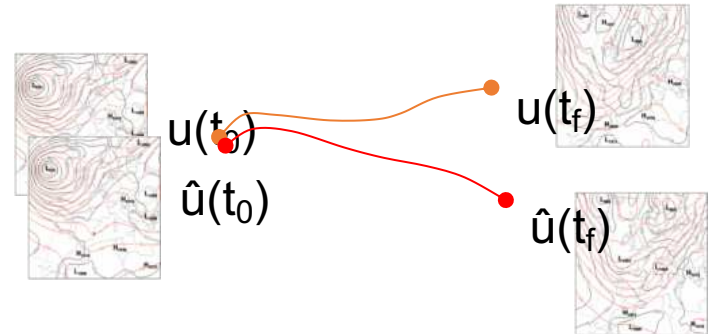


ABSTRACT

It is proposed that certain formally deterministic fluid systems which possess many scales of motion are observationally indistinguishable from indeterministic systems; specifically, that two states of the system differing initially by a small “observational error” will evolve into two states differing as greatly as randomly chosen states of the system within a finite time interval, which cannot be lengthened by reducing the amplitude of the initial error.

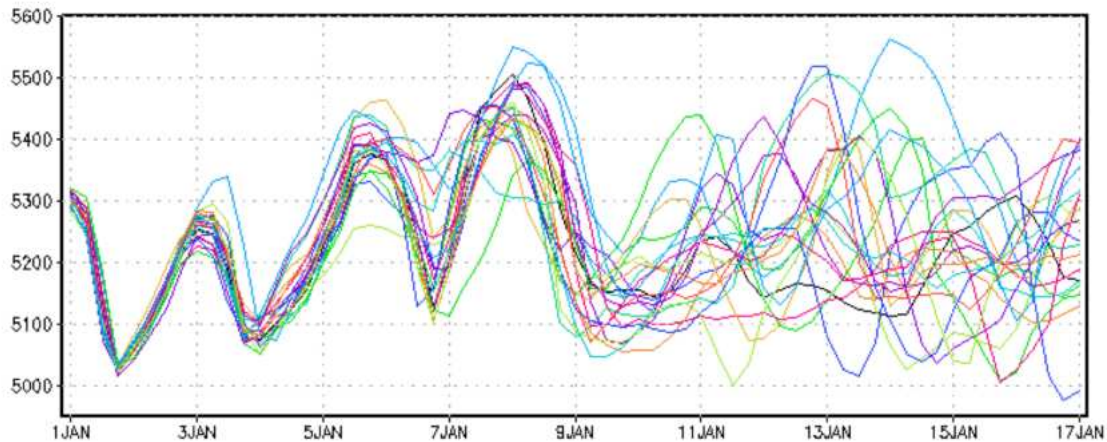
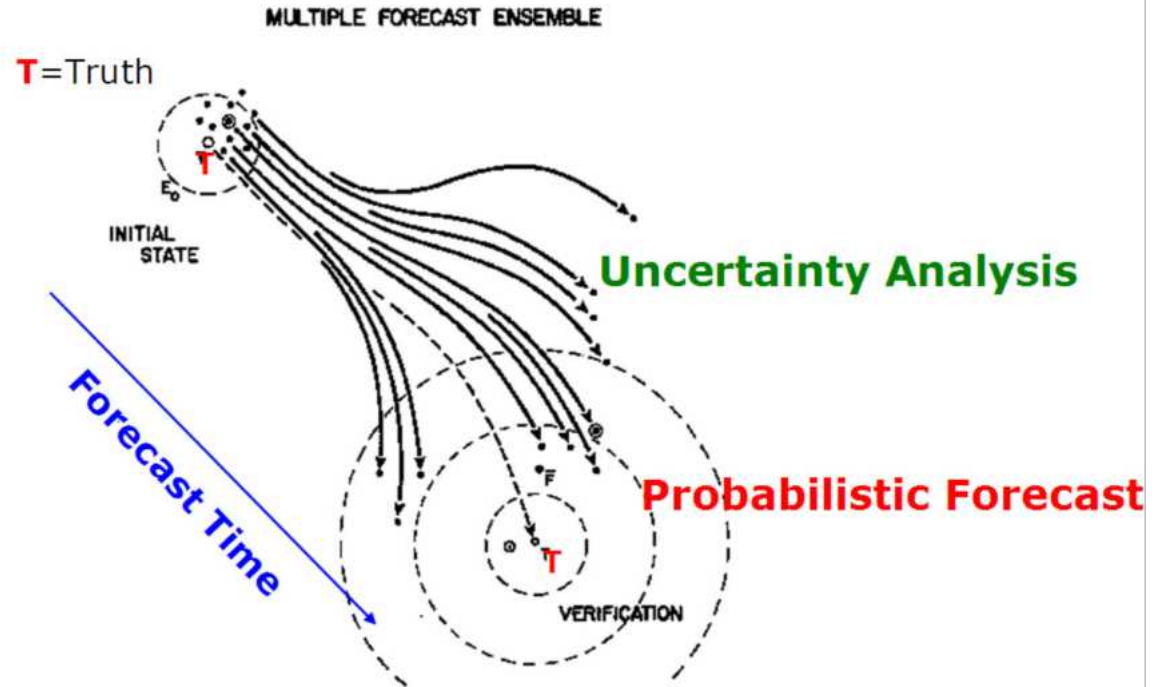


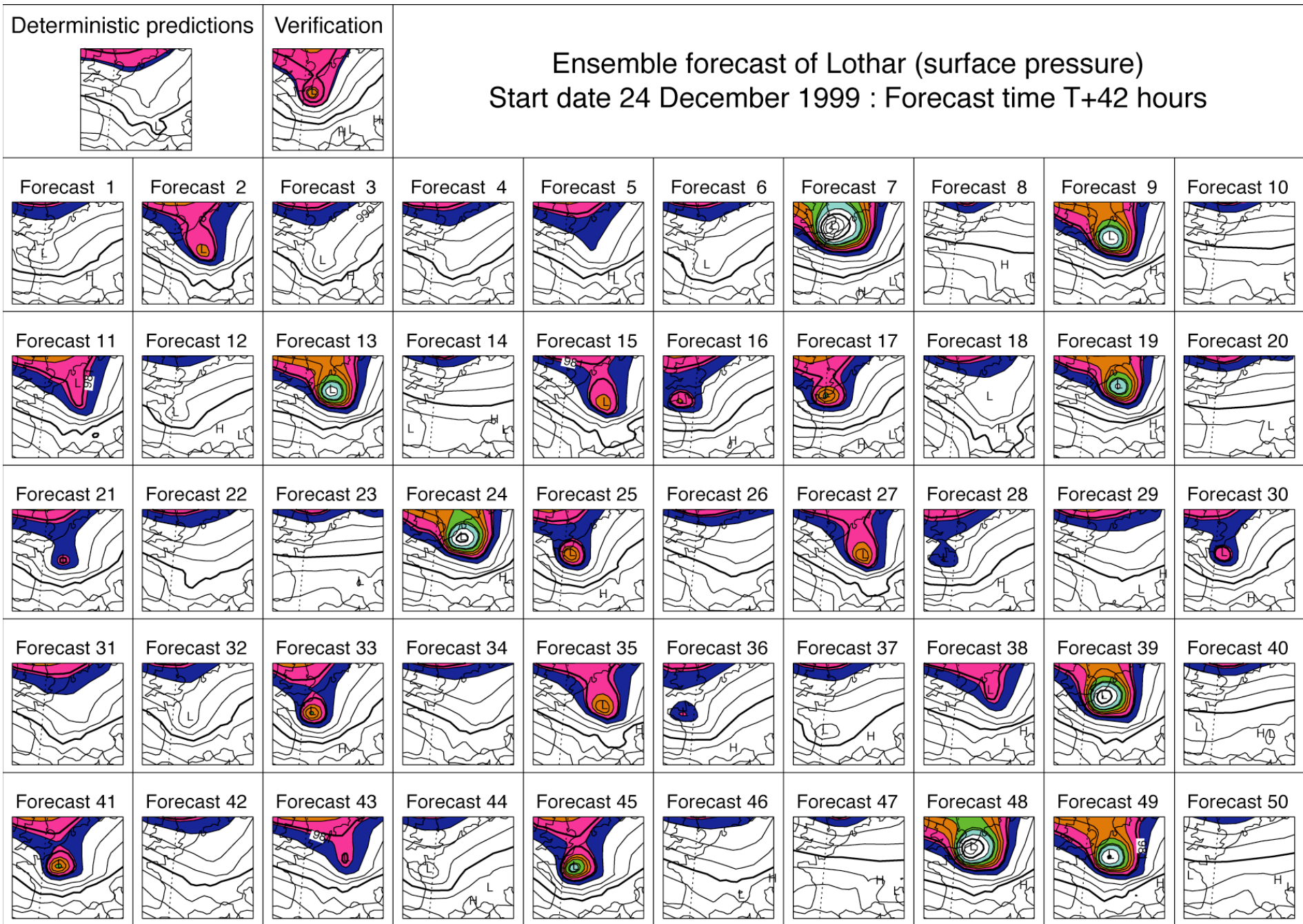
Pierre-Simon Laplace, « Essai philosophique sur les probabilités » (1819)



How can we go beyond that limit then?

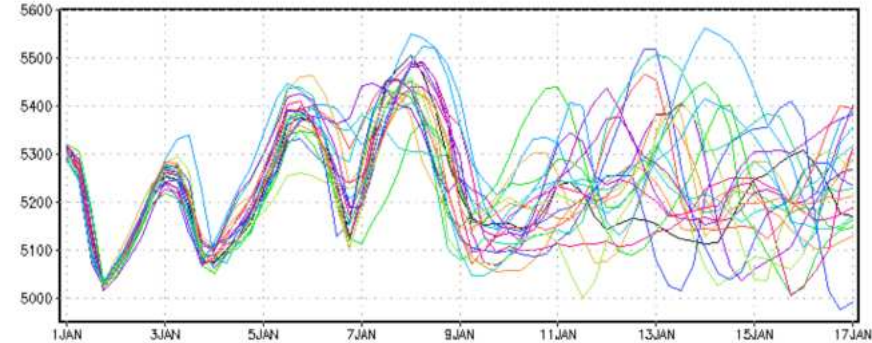
Ensemble forecast



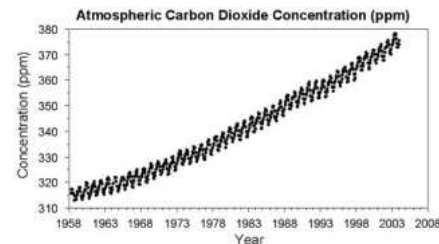
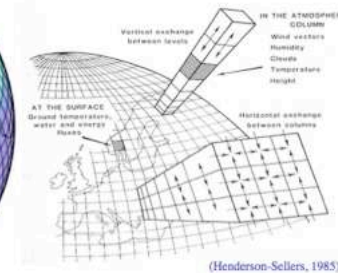
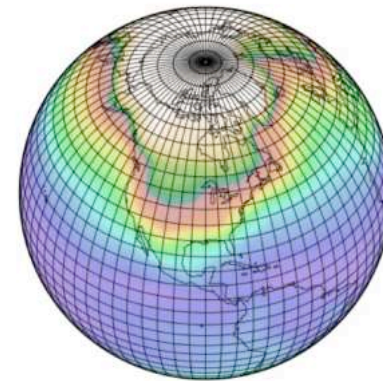


What about the Climate then? Climate prediction is more like a boundary conditions problem

Long integrations of climate models forget the initial conditions. Predicting the climate consists in predicting the statistical characteristics of the climate system, in a different equilibrium, imposed by external conditions. We rather talk about climate “projection”



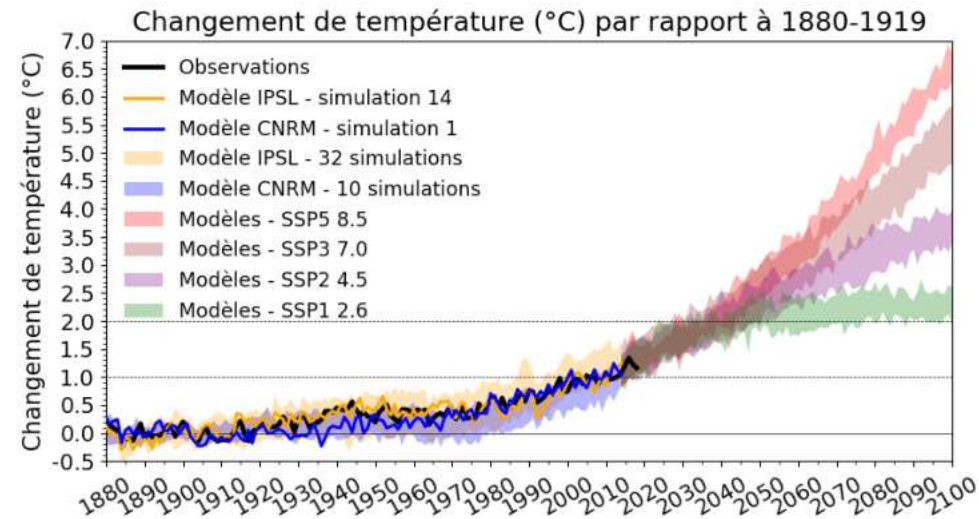
Processes	Timescale											
	days		years			thousands of years			millions of years			
	h/d	w	m	y	10 y	10 ² y	10 ³ y	10 ⁴ y	10 ⁵ y	10 ⁶ y	10 ⁹ y	
weather	■	■										
land surface	■	■	■									
ocean mixed layer	■	■	■									
sea ice		■	■	■								
volcanos		■	■	■								
vegetation	■	■	■	■	■	■	■	■	■	■		
thermocline				■	■	■	■	■	■	■		
mountain glaciers					■	■	■	■	■	■		
deep ocean						■	■	■	■	■		
ice sheets						■	■	■	■	■		
orbital forcing								■	■	■		
tectonics										■	■	
weathering									■	■	■	
solar "constant"			■	■	■	■	■	■	■	■	■	■



What about the Climate then? Climate prediction is more like a boundary conditions problem

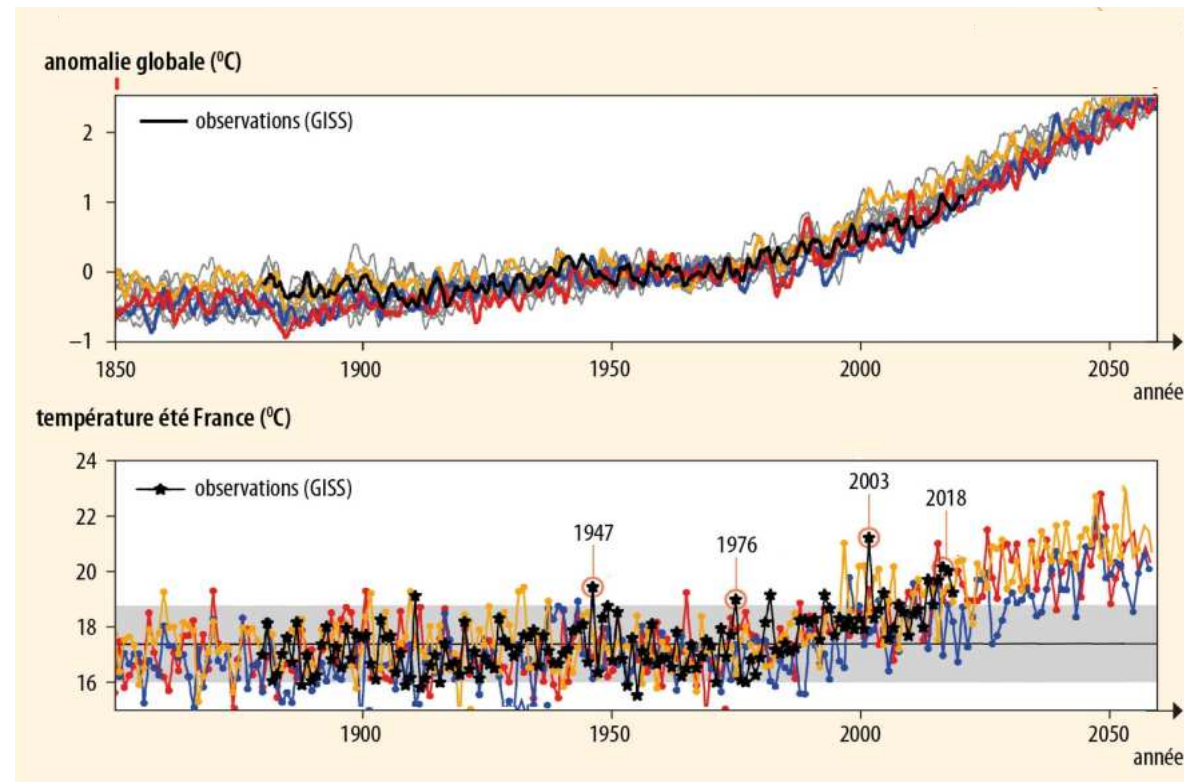
Uncertainty in climate prediction is incompressible, due to the chaotic nature of the system.

Since the error on the initial conditions no longer counts, the error due to the formulation of the model becomes more important



What about the Climate then? Climate prediction is more like a boundary conditions problem

The evolution of the weather observed over a period is only one of the possible evolutions in a certain climate.

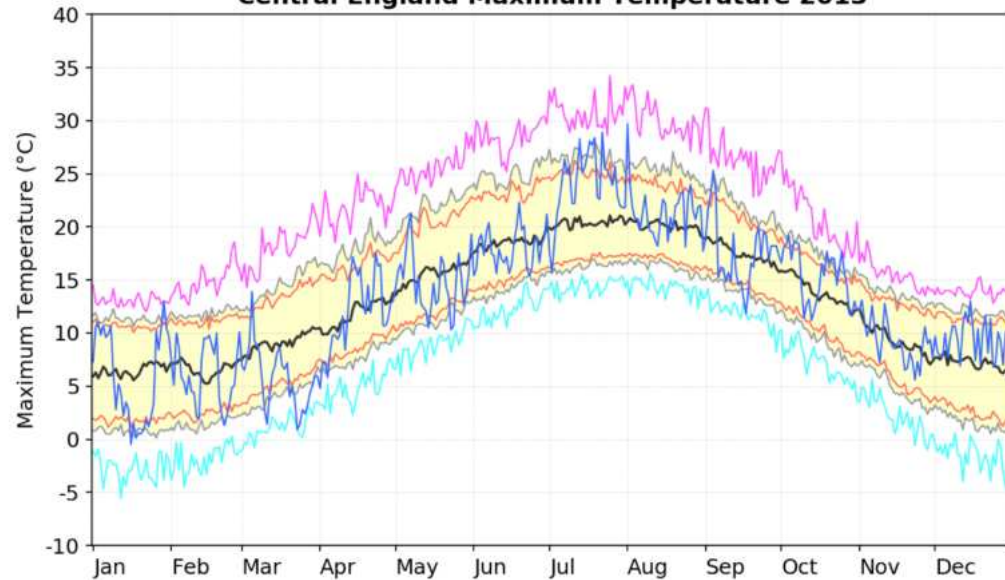


Time series of meteorological variables => **statistical characteristics**
(mean, standard deviation, extremes, percentiles, etc.)

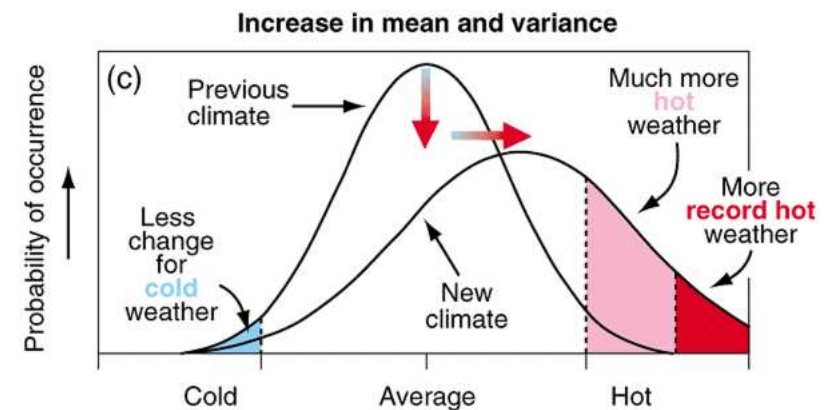
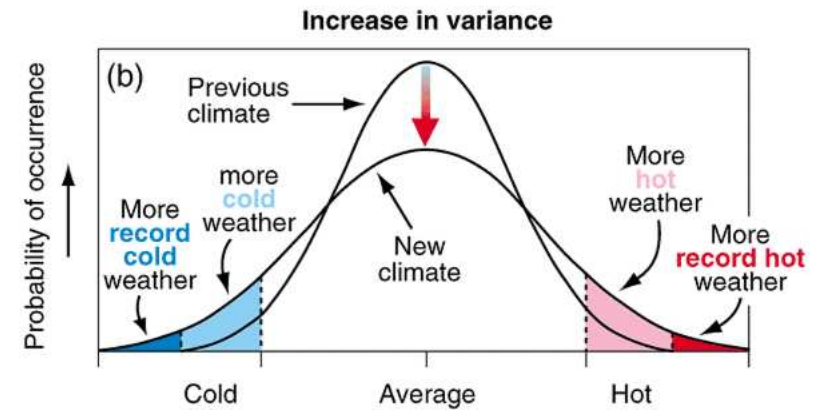
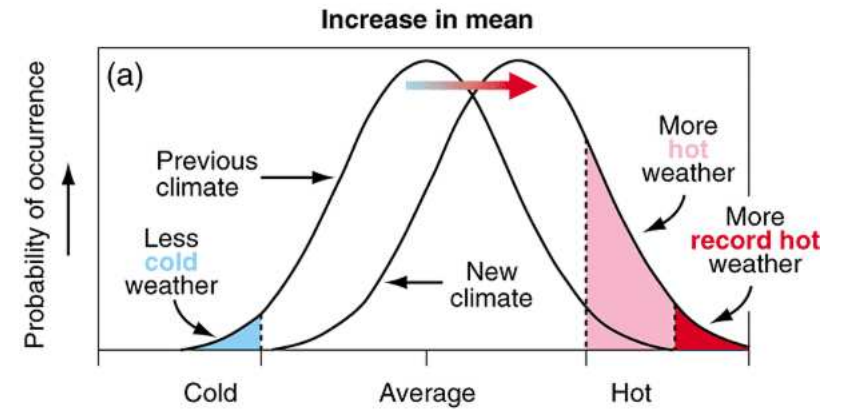
Met Office

Source: HadCET Creation Date: 07/04/2022 13:40 © Crown copyright

Central England Maximum Temperature 2013

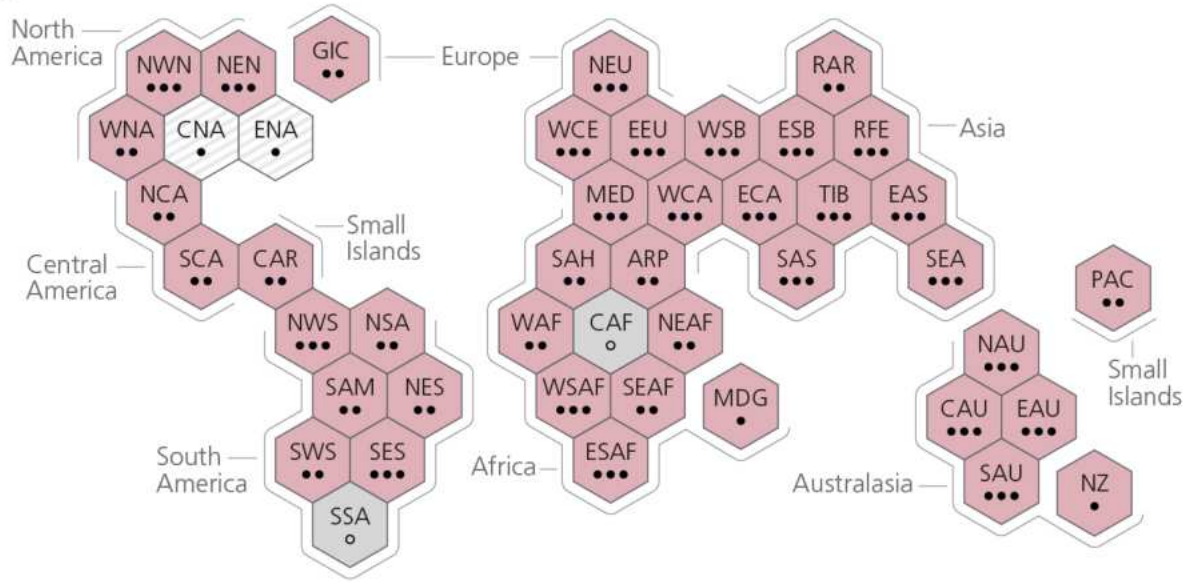


— 1961-1990 — lowest — 5% — 10% — 90% — 95% — highest — daily CET

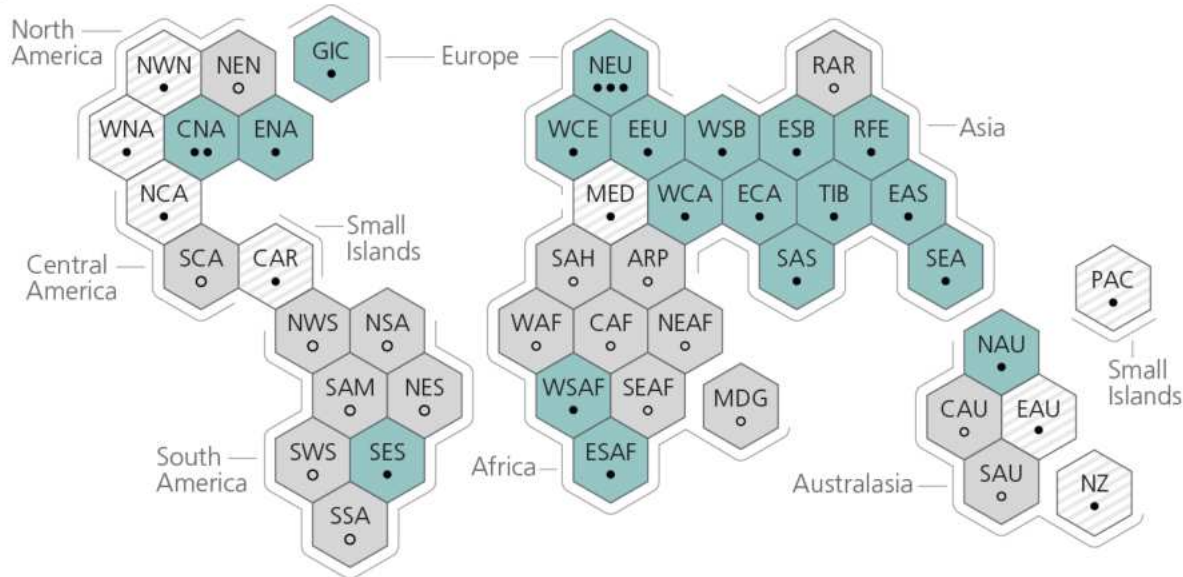


a) **Synthesis of assessment of observed change in hot extremes, heavy precipitation and drought, and confidence in human contribution to the observed changes in the world's regions**

Hot extremes ← including heatwaves



Heavy precipitation



Dimension of Risk: Hazard

Key

Type of observed change since the 1950s

Increase

Decrease

Limited data and/or literature

Low agreement in the type of change

Confidence in human contribution to the observed change

••• High

•• Medium

• Low due to limited agreement

○ Low due to limited evidence

Each hexagon corresponds to a region

North-Western North America

IPCC AR6 WGI reference regions:

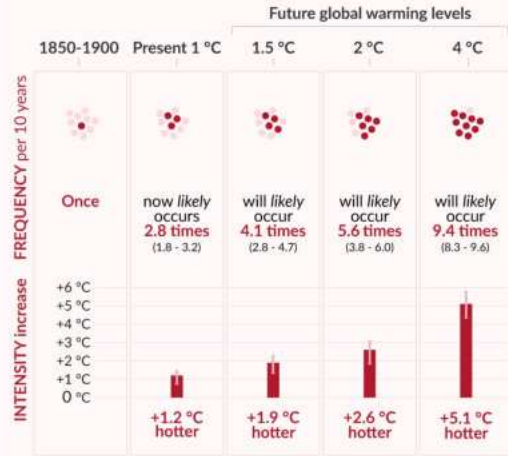
North America: **NWN** (North-Western North America), **NEN** (North-Eastern North America), **WNA** (Western North America), **CNA** (Central North America), **ENA** (Eastern North America), **Central America:** **NCA** (Northern Central America), **SCA** (Southern Central America), **CAR** (Caribbean), **South America:** **NWS** (North-Western South America), **NSA** (Northern South America), **NES** (North-Eastern South America), **SAM** (South American Monsoon), **SWS** (South-Western South America), **SES** (South-Eastern South America), **SSA** (Southern South America), **Europe:** **GIC** (Greenland/Iceland), **NEU** (Northern Europe), **WCE** (Western and Central Europe), **EEU** (Eastern Europe), **MED** (Mediterranean), **Africa:** **MED** (Mediterranean), **SAH** (Sahara), **WAF** (Western Africa), **CAF** (Central Africa), **NEAF** (North Eastern Africa), **SEAF** (South Eastern Africa), **WSAF** (West Southern Africa), **ESAF** (East Southern Africa), **MDG** (Madagascar), **Asia:** **RAR** (Russian Arctic), **WSB** (West Siberia), **ESB** (East Siberia), **RFE** (Russian Far East), **WCA** (West Central Asia), **ECA** (East Central Asia), **TIB** (Tibetan Plateau), **EAS** (East Asia), **ARP** (Arabian Peninsula), **SAS** (South Asia), **SEA** (South East Asia), **Australasia:** **NAU** (Northern Australia), **CAU** (Central Australia), **EAU** (Eastern Australia), **SAU** (Southern Australia), **NZ** (New Zealand), **Small Islands:** **CAR** (Caribbean), **PAC** (Pacific Small Islands)

Projected changes in extremes are larger in frequency and intensity with every additional increment of global warming

Hot temperature extremes over land

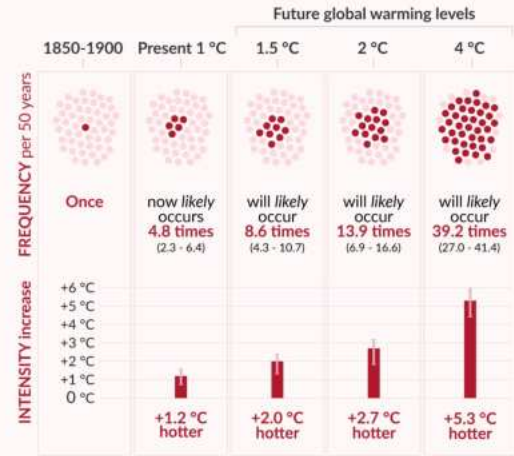
10-year event

Frequency and increase in intensity of extreme temperature event that occurred **once in 10 years** on average in a climate without human influence



50-year event

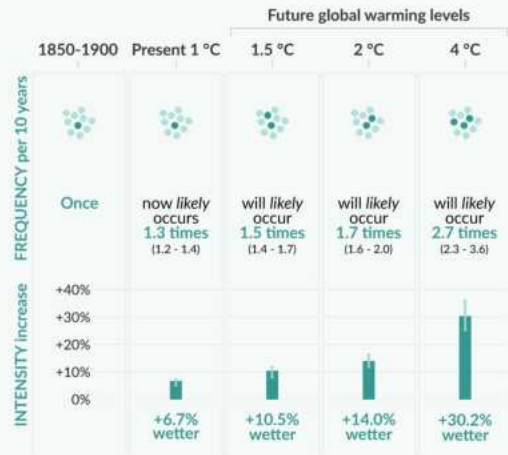
Frequency and increase in intensity of extreme temperature event that occurred **once in 50 years** on average in a climate without human influence



Heavy precipitation over land

10-year event

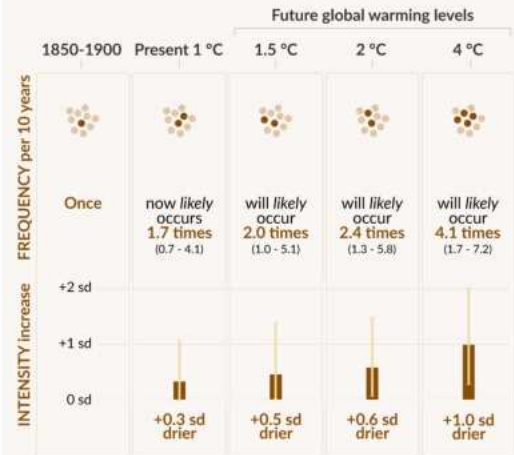
Frequency and increase in intensity of heavy 1-day precipitation event that occurred **once in 10 years** on average in a climate without human influence



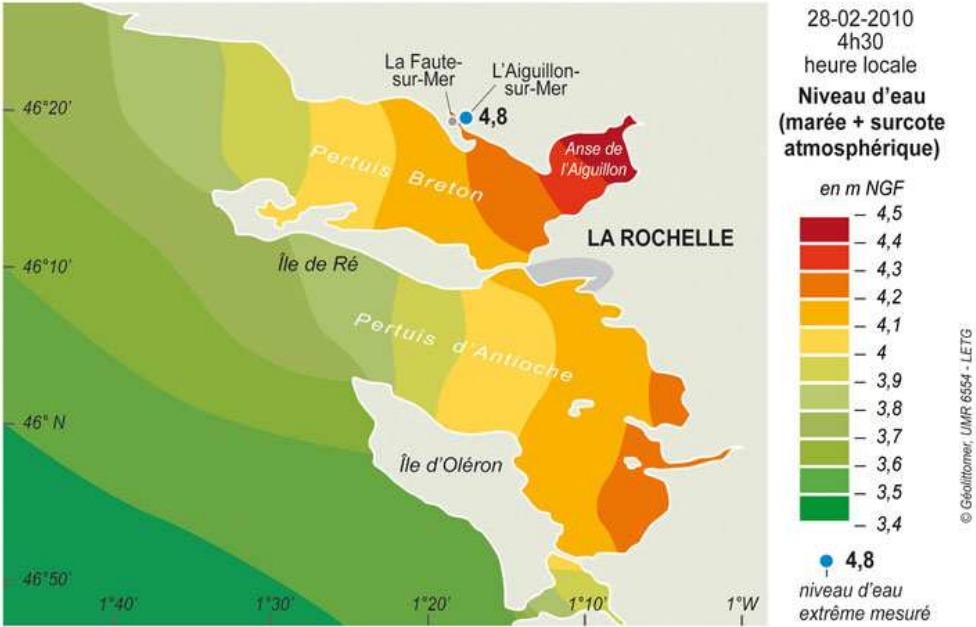
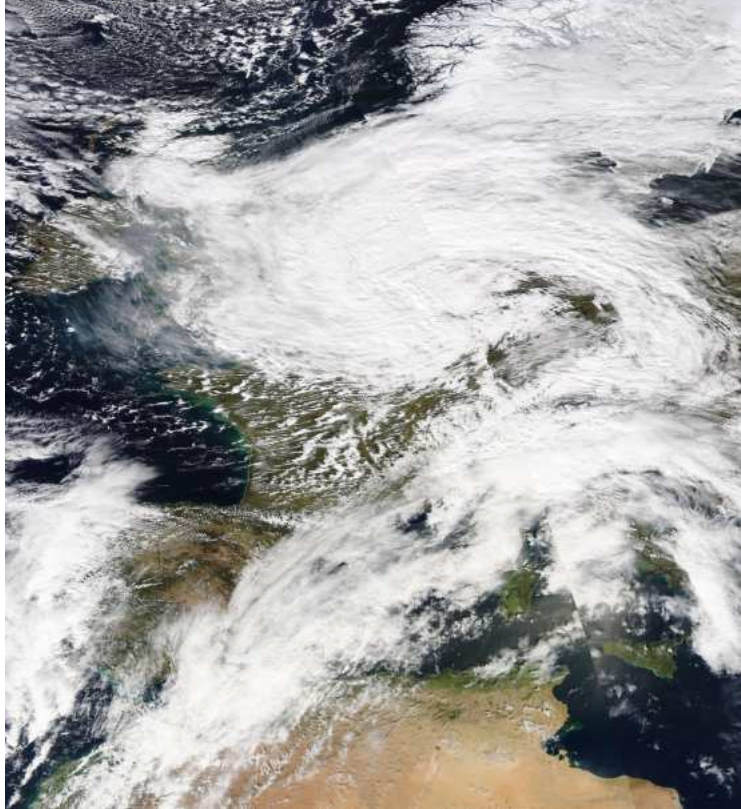
Agricultural & ecological droughts in drying regions

10-year event

Frequency and increase in intensity of an agricultural and ecological drought event that occurred **once in 10 years** on average across drying regions in a climate without human influence



Cyclone Xynthia, february 2010



Probability (return times y^{-1}):

- +20cm (today) : 200
- +50cm (around 2060) : 50
- +1m (2100) : 2

Sources : carte de simulation des niveaux d'eau établie par le BRGM (mars 2010, BRGM/RP-58261-FR, p36.)
niveau d'eau extrême mesuré dans le bourg de l'Aiguillon selon rapport CGEDD (16 sept. 2010, Mission n°007336-01, p21.)

Summary:

1) Weather forecasting is a problem with initial conditions. Due to the non-linear and chaotic nature of the atmosphere, the weather forecast is limited in time, probably around 15 days.

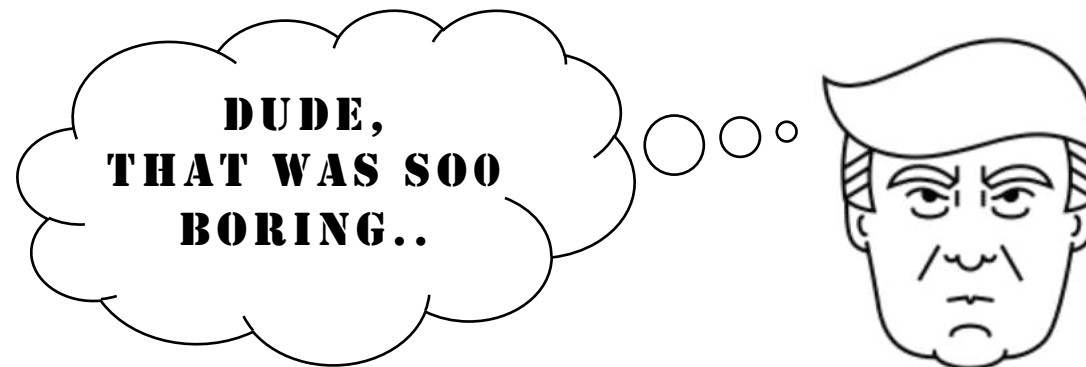
2) Climate prediction “forgets” its initial conditions. It predicts probability distributions of the state of the system in a new equilibrium.

3) Meteorological events can hence be forecasted deterministically up to a few days in advance, while we can predict the changes in their statistical characteristics in a modified climate



Summary:

- 1) Weather forecasting is a problem with initial conditions. Due to the non-linear and chaotic nature of the atmosphere, the weather forecast is limited in time, probably around 15 days.
- 2) Climate prediction “forgets” its initial conditions. It predicts probability distributions of the state of the system in a new equilibrium.
- 3) Meteorological events can hence be forecasted deterministically up to a few days in advance, while we can predict the changes in their statistical characteristics in a modified climate



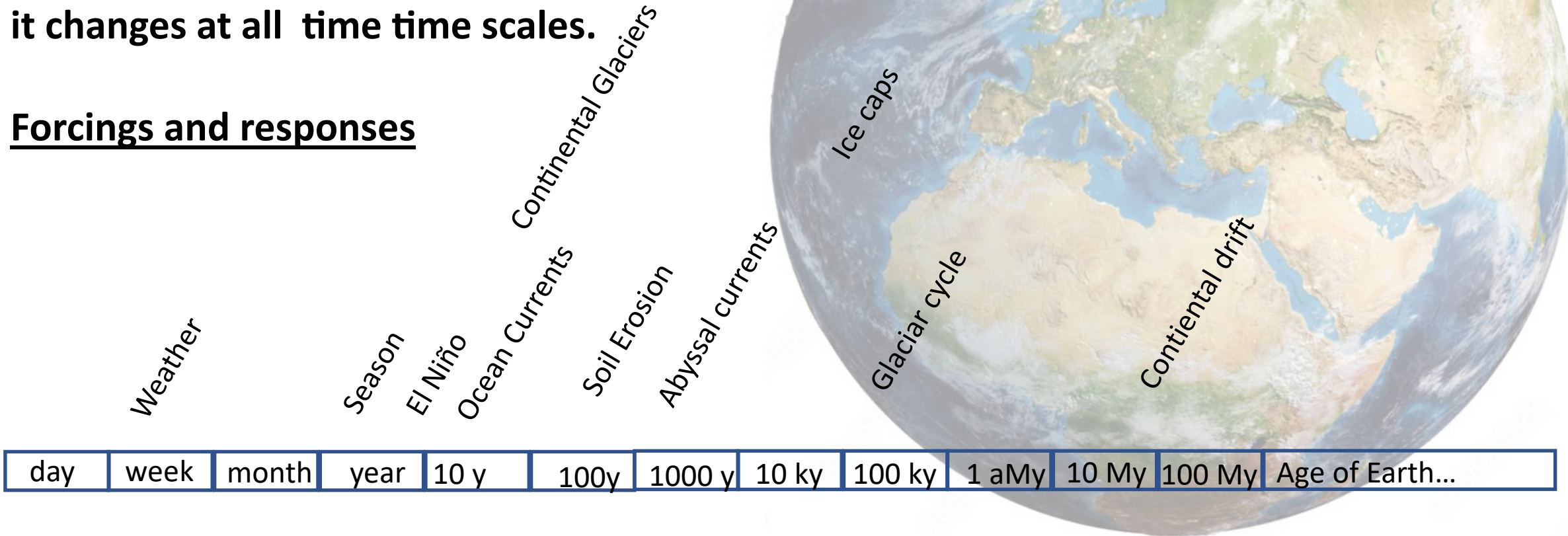
Reserve slides

Climate

Variations in the Earth's climate result from responses to forcings on very diverse time scales.

**The climate system is evolving:
it changes at all time scales.**

Forcings and responses

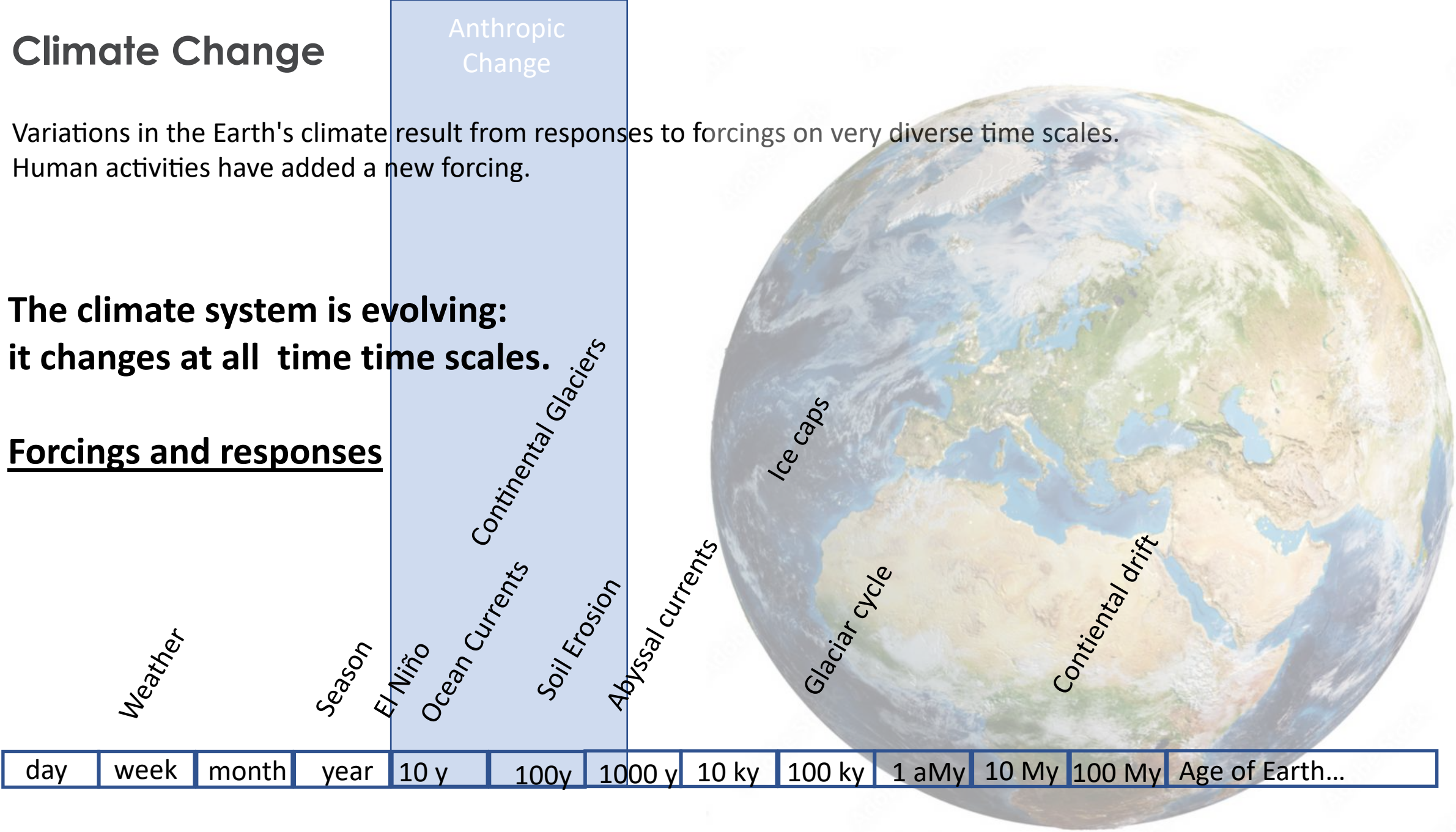


Climate Change

Variations in the Earth's climate result from responses to forcings on very diverse time scales. Human activities have added a new forcing.

**The climate system is evolving:
it changes at all time scales.**

Forcings and responses

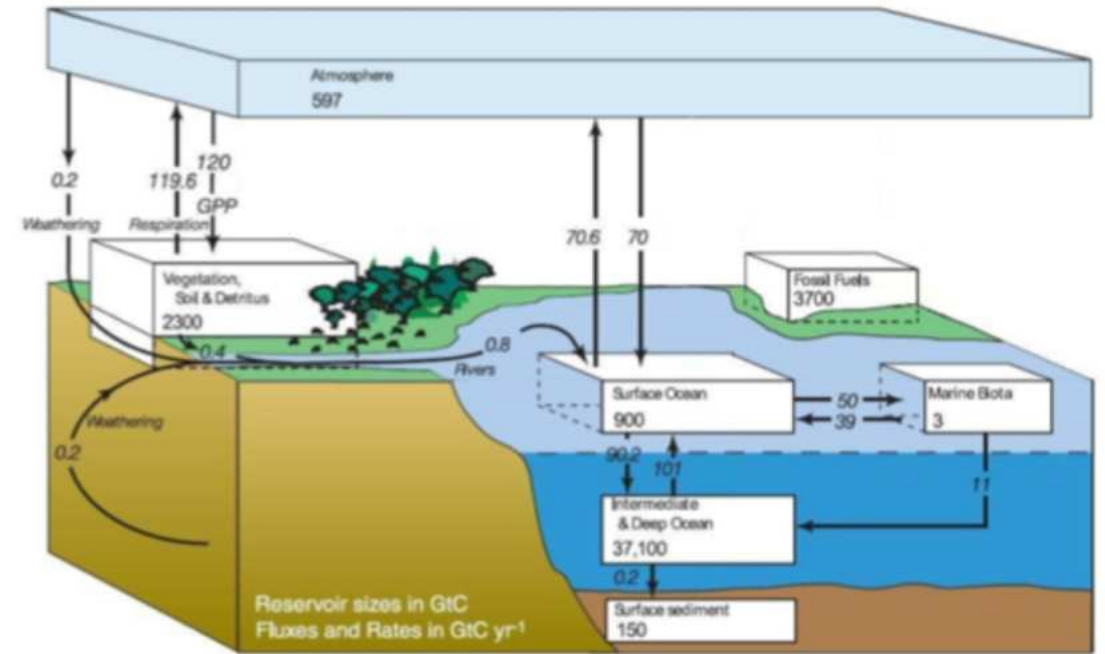
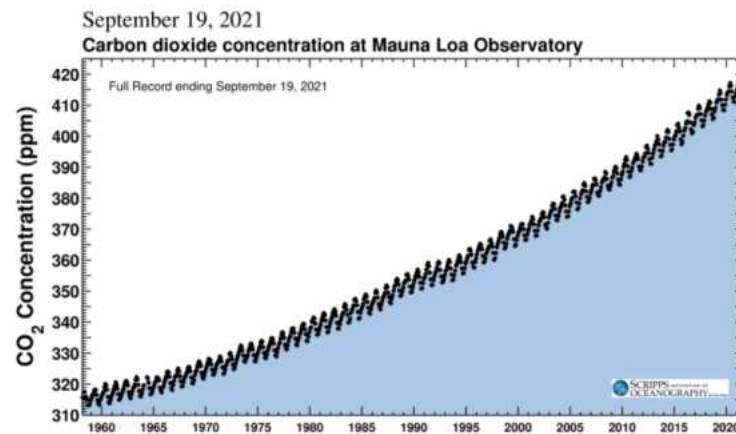


Changement ?

Les variations du climat de la Terre résultent de la réponse à des forçages, à des échelles de temps très diverses. Les activités humaines ont rajouté un **nouveau forçage**.

Cycle du carbone

Réservoirs : GtC Fluxes GtC/year



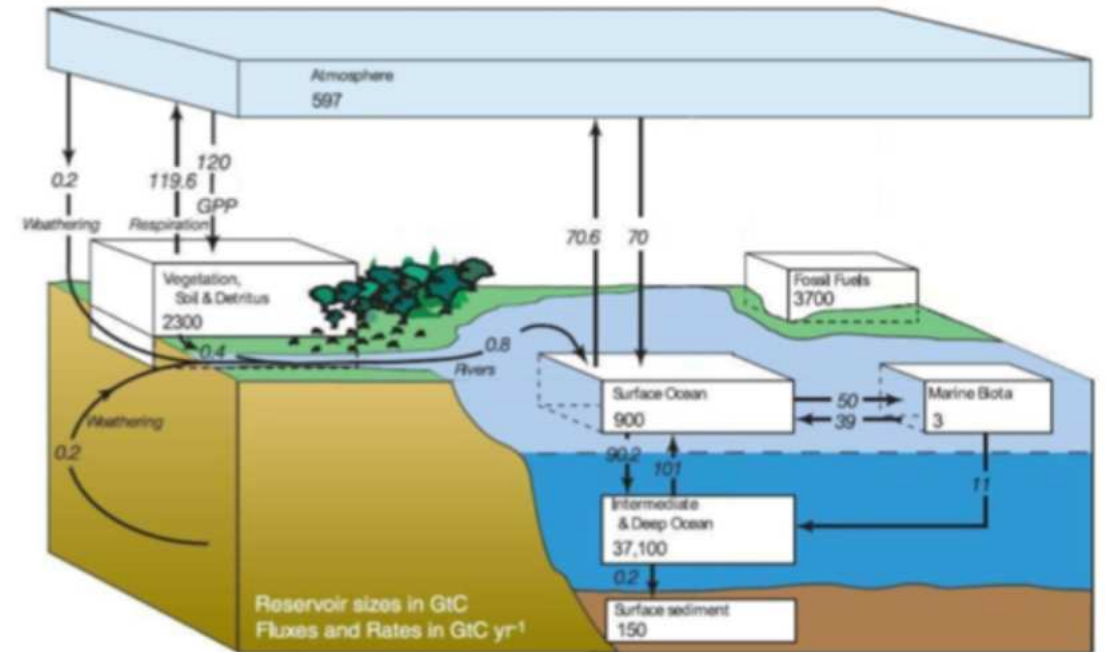
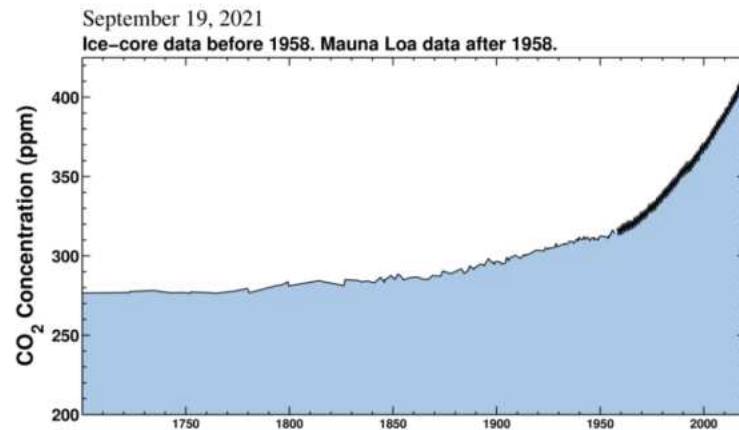
« carbone » dans Le Système Périodique de Primo Levi. *Albin Michel*

Changement ?

Les variations du climat de la Terre résultent de la réponse à des forçages, à des échelles de temps très diverses. Les activités humaines ont rajouté un **nouveau forçage**.

Cycle du carbone

Réservoirs : GtC Fluxes GtC/year



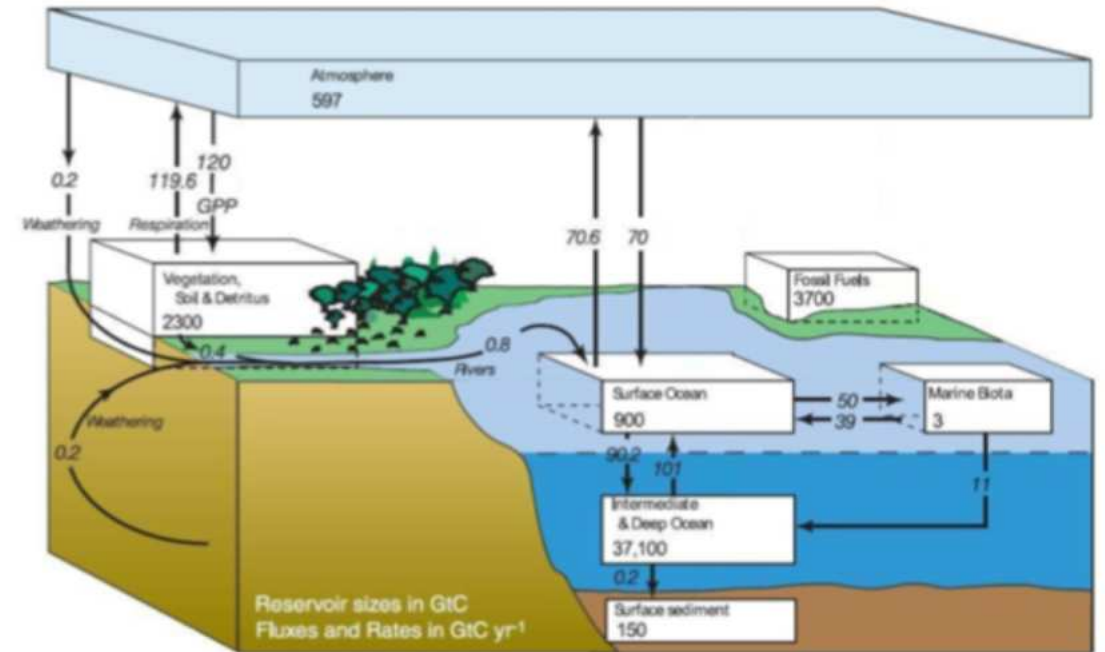
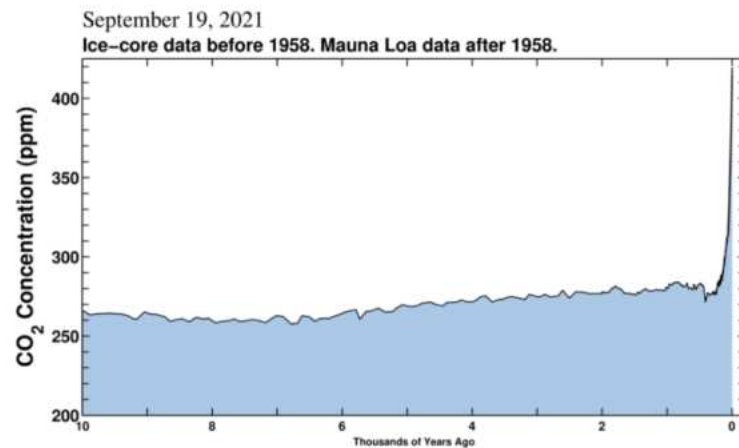
« carbone » dans Le Système Périodique de Primo Levi. *Albin Michel*

Changement ?

Les variations du climat de la Terre résultent de la réponse à des forçages, à des échelles de temps très diverses.
Les activités humaines ont rajouté un **nouveau forçage**.

Cycle du carbone

Réservoirs : GtC Fluxes GtC/year

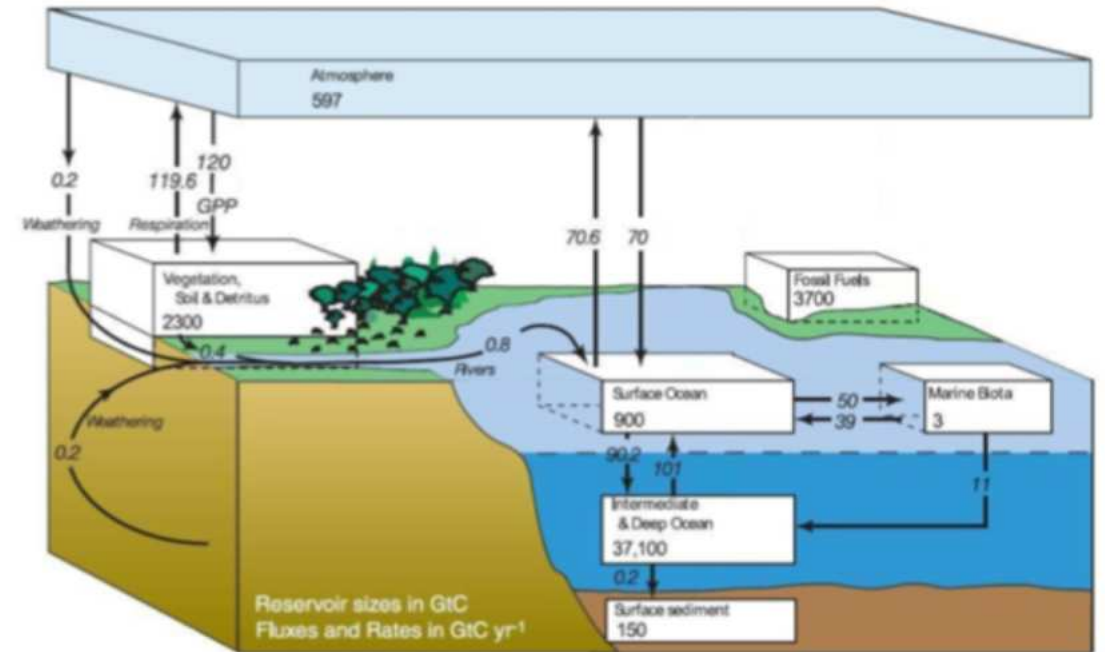
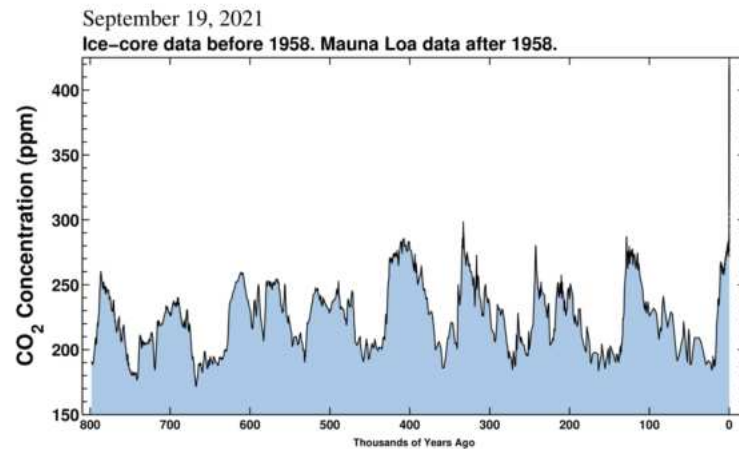


Changement ?

Les variations du climat de la Terre résultent de la réponse à des forçages, à des échelles de temps très diverses. Les activités humaines ont rajouté un **nouveau forçage**.

Cycle du carbone

Réservoirs : GtC Fluxes GtC/year



« carbone » dans Le Système Périodique de Primo Levi. *Albin Michel*

Changement ?

Les variations du climat de la Terre résultent de la réponse à des forçages, à des échelles de temps très diverses. Les activités humaines ont rajouté un **nouveau forçage**.

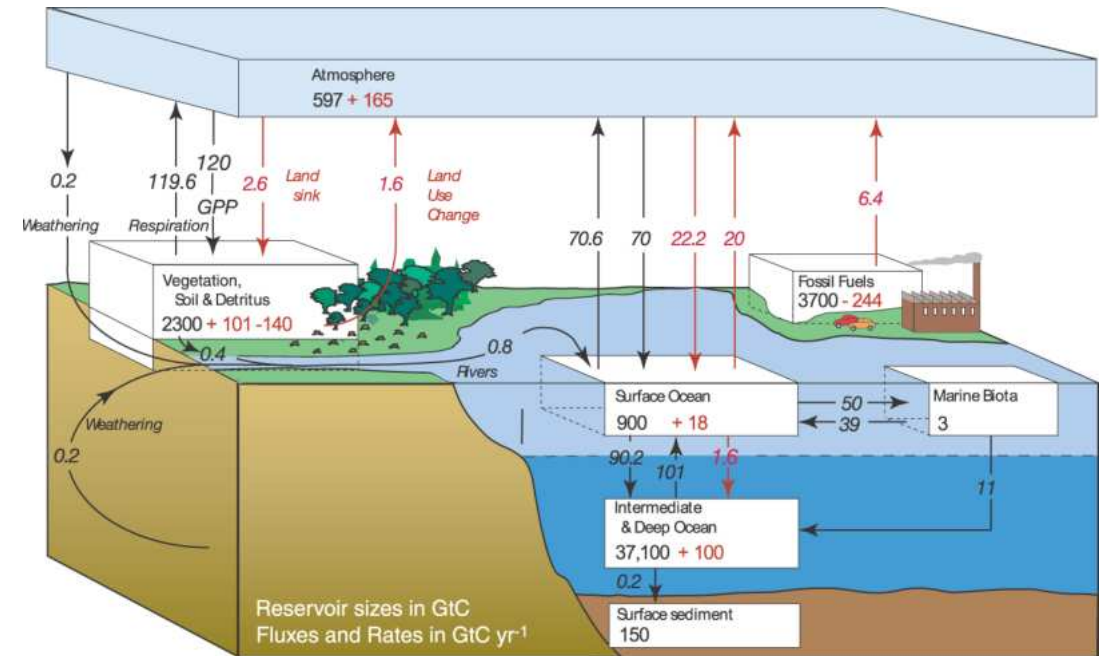
Cycle du carbone **perturbé**

Le carbone est émis par la combustion des fluides fossiles et par la déforestation. Environ la moitié reste dans l'atmosphère.

Le reste traverse les océans et les sols peu profonds, qui échangent des flux importants avec l'atmosphère.

Le flux de stockage dans les sédiments est très faible par rapport au flux anthropique. Un an de production \Leftrightarrow 30 ans de stockage.

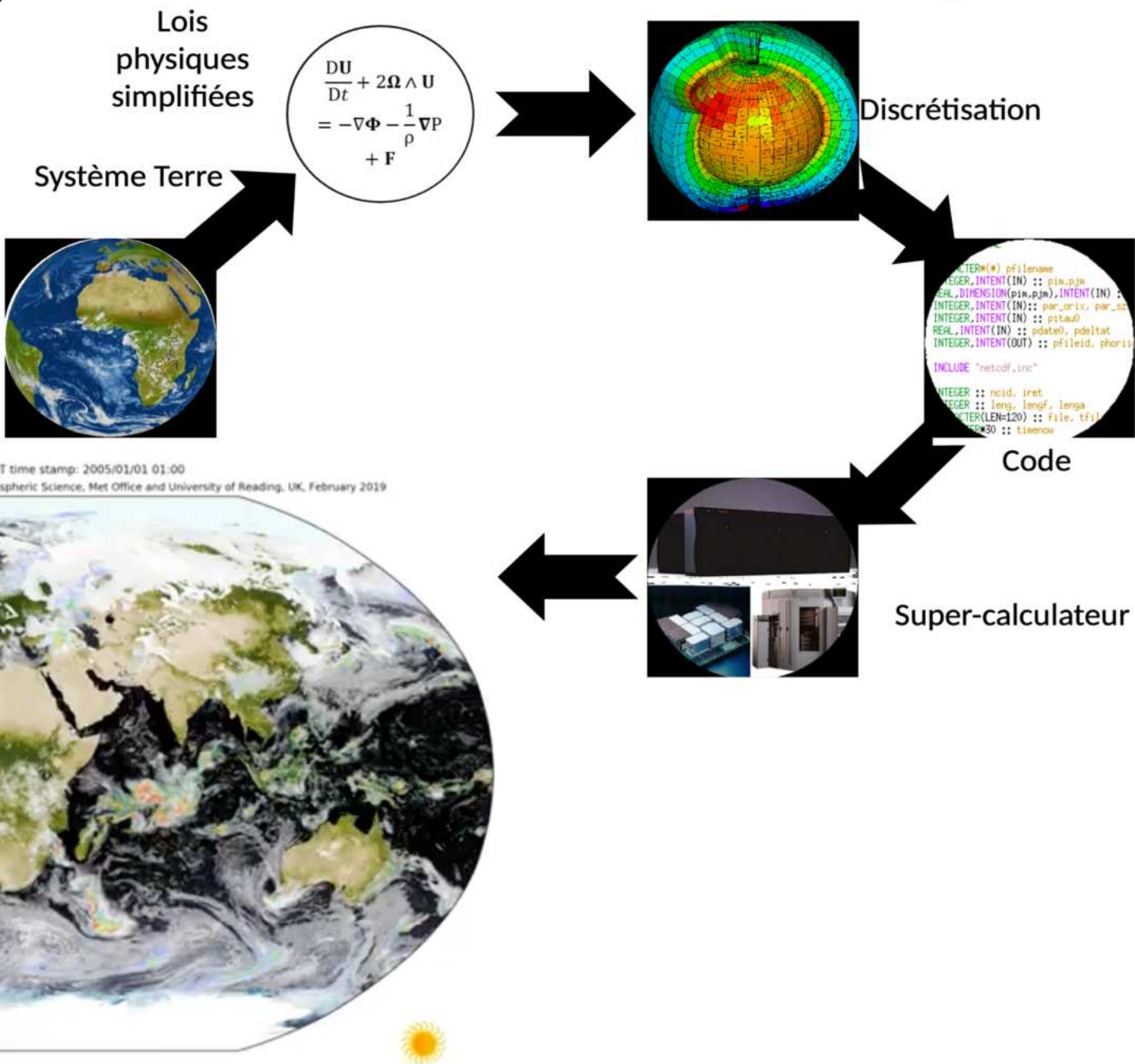
L'excès de carbone restera dans l'atmosphère pendant des siècles.



Et comment on connait tout ca?

Les GCM

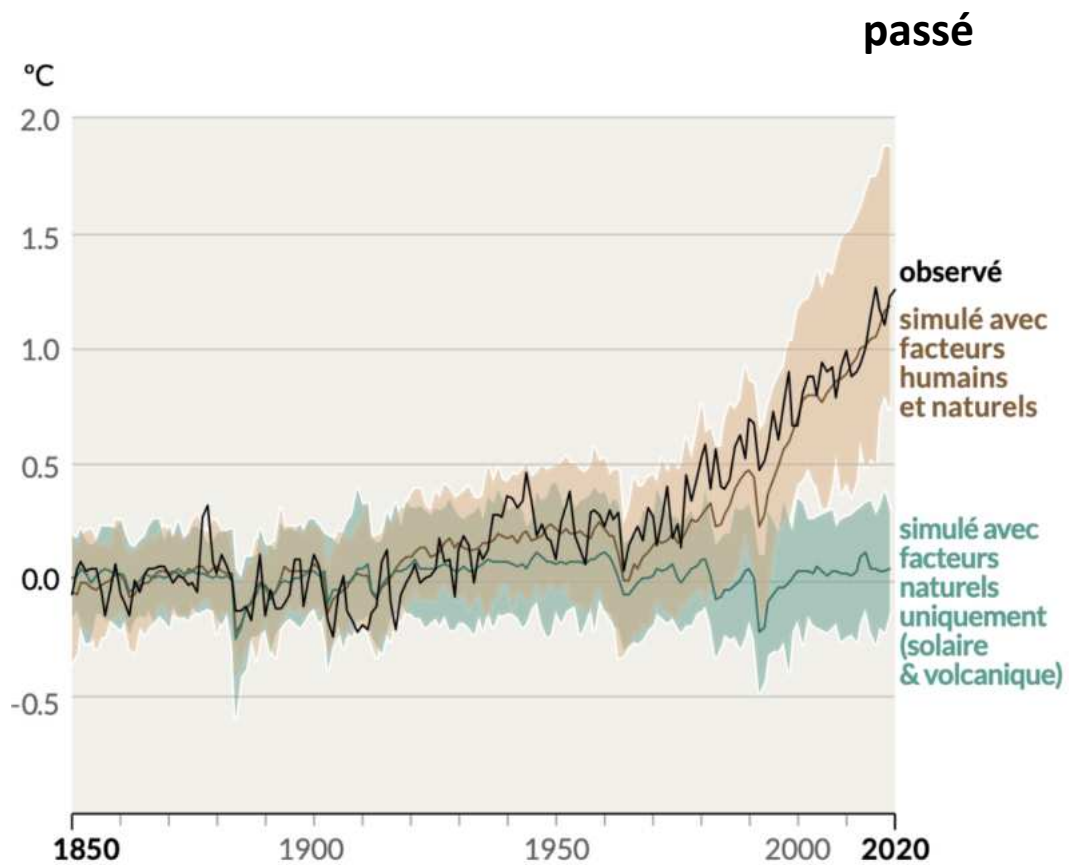
General Circulation Models
Global Climate Models



Et comment on connait tout ca?

Les GCM

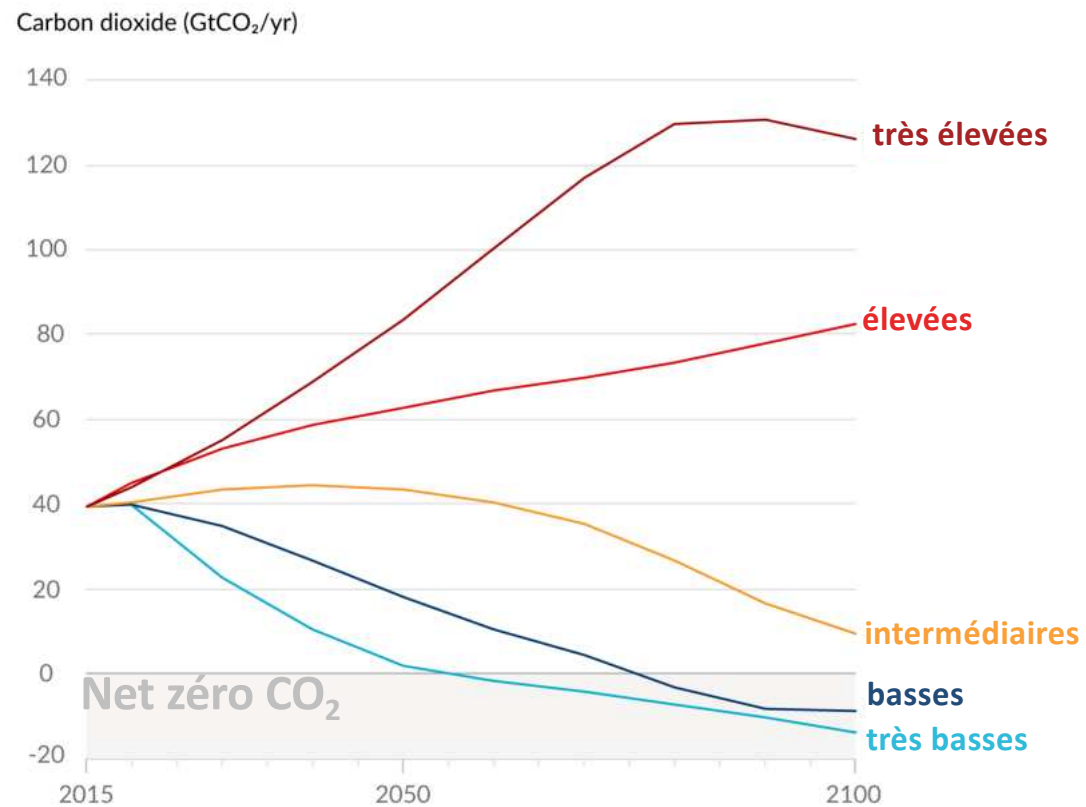
Comment utilise-t-on les Global Climate Models ?



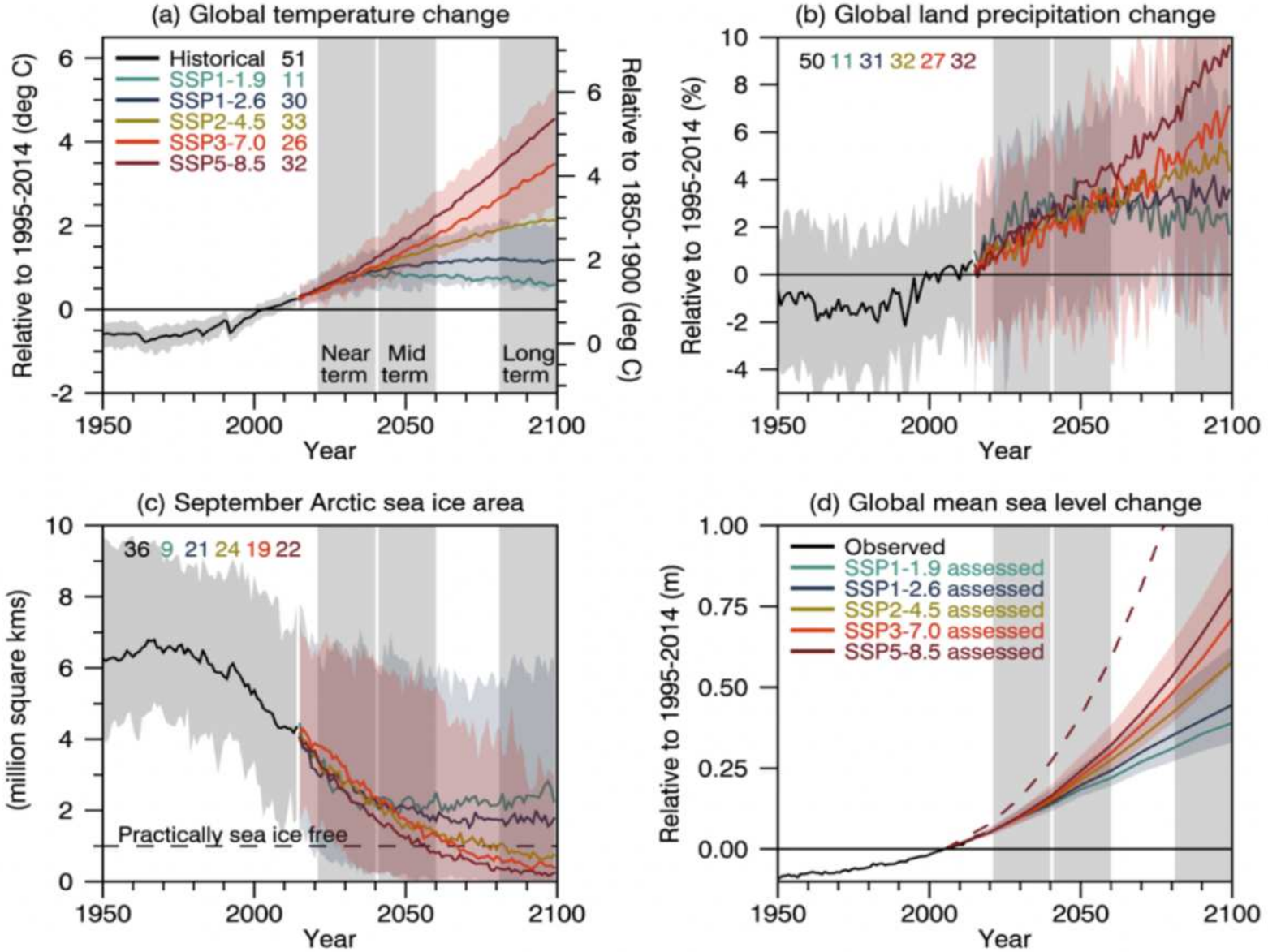
futur

Scenarios => Emissions

Emissions de CO₂ (Gt/an)



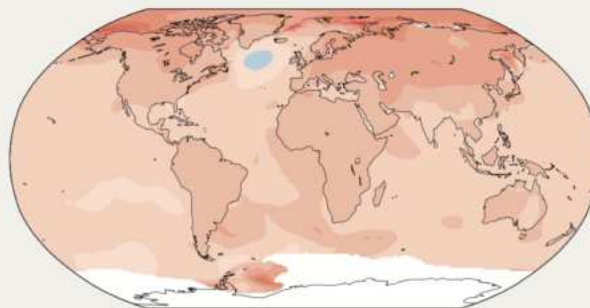
Quelques prévisions climatiques à partir des scénarios, tirés du dernier rapport du GIEC (2021)



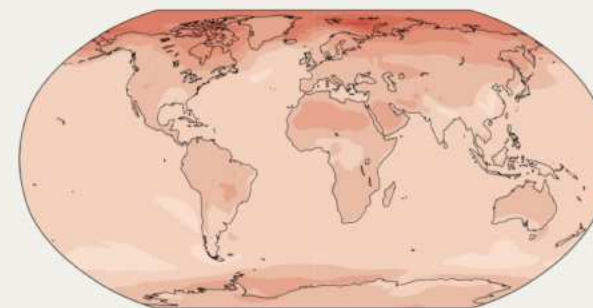
(a) Changement de la température moyenne annuelle (°C) pour un réchauffement planétaire de 1 °C

Tous les continents sont affectés par le réchauffement de 1 °C, généralement plus prononcé au-dessus des terres émergées que de l'océan, tant dans les observations que les modèles. Les structures des changements observés et simulés sont cohérentes pour la plupart des régions.

Changement observé pour 1°C de réchauffement planétaire



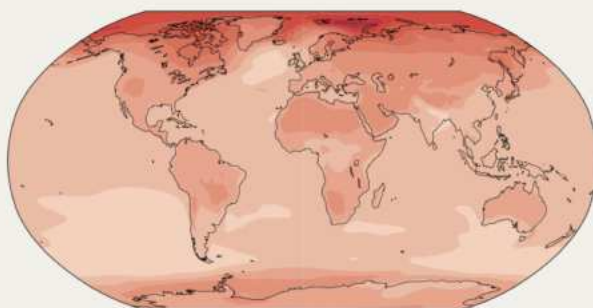
Changement simulé pour 1 °C de réchauffement planétaire



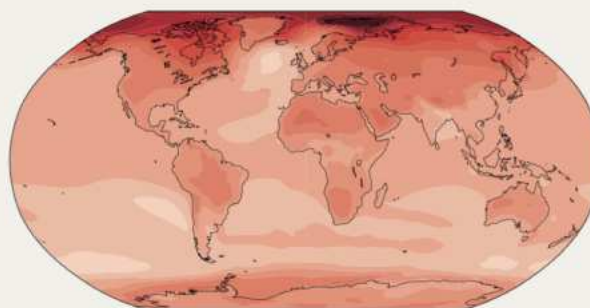
(b) Changement de la température moyenne annuelle (°C) par rapport à 1850–1900

Quel que soit le niveau de réchauffement, les terres émergées se réchauffent davantage que les zones océaniques, et l'Arctique et l'Antarctique se réchauffent davantage que les tropiques.

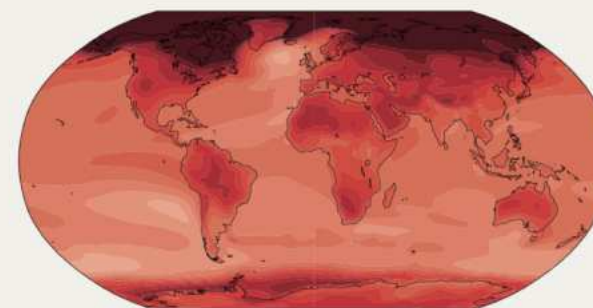
Changement simulé pour 1,5 °C de réchauffement planétaire



Changement simulé pour 2 °C de réchauffement planétaire



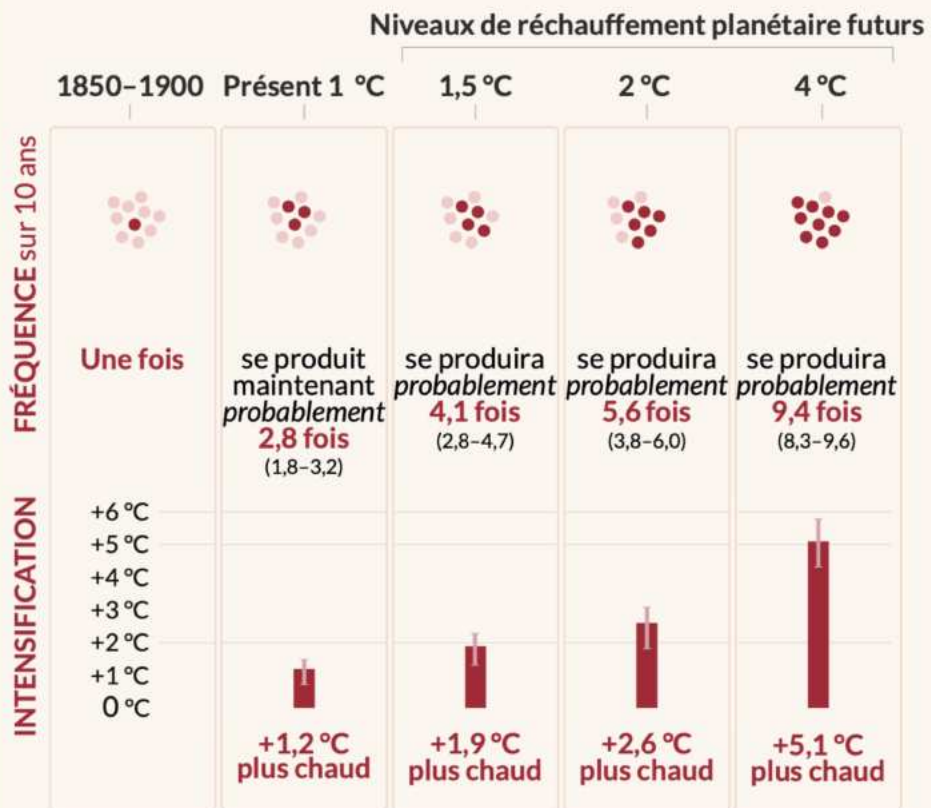
Changement simulé pour 4 °C de réchauffement planétaire



Extrêmes chauds au-dessus des terres émergées

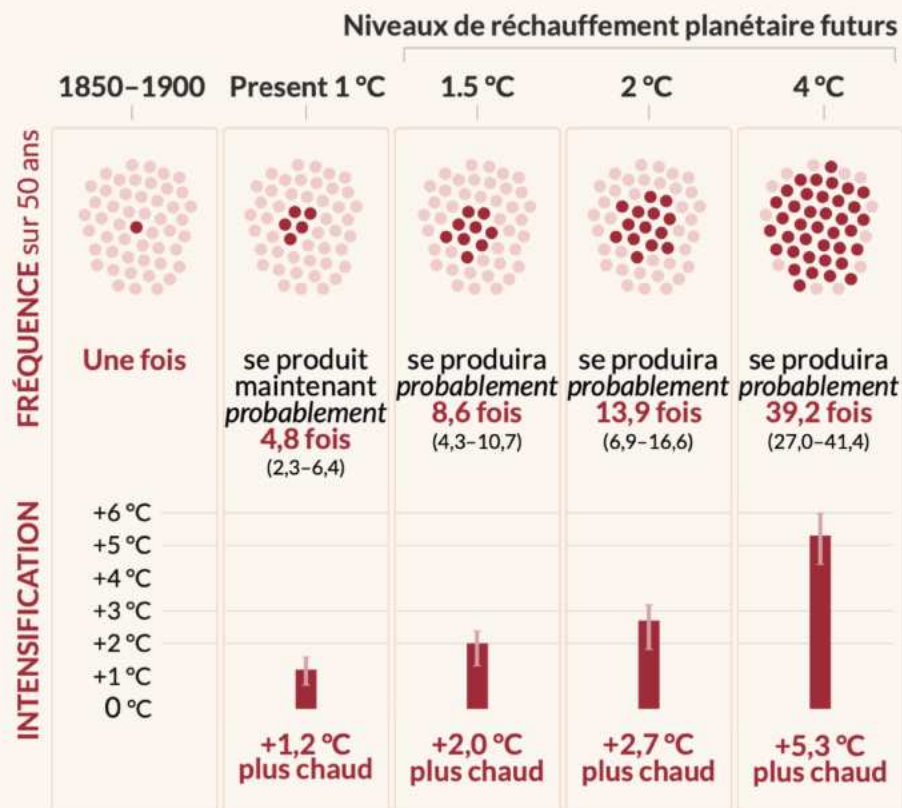
Evènement décennal

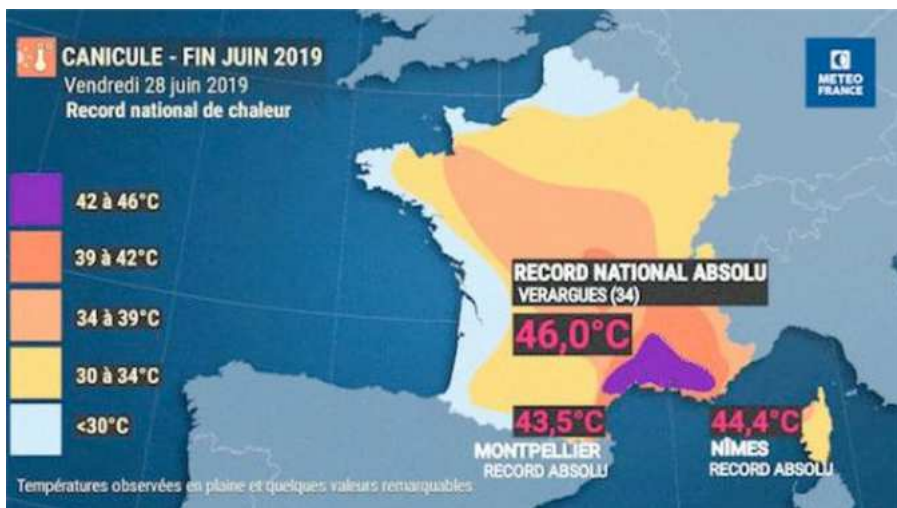
Augmentation de la fréquence et de l'intensité d'un évènement de température extrême qui se produisait **une fois tous les 10 ans** en moyenne dans un climat sans influence humaine.



Evènement cinquantennal

Augmentation de la fréquence et de l'intensité d'un évènement de température extrême qui se produisait **une fois tous les 50 ans** en moyenne dans un climat sans influence humaine.





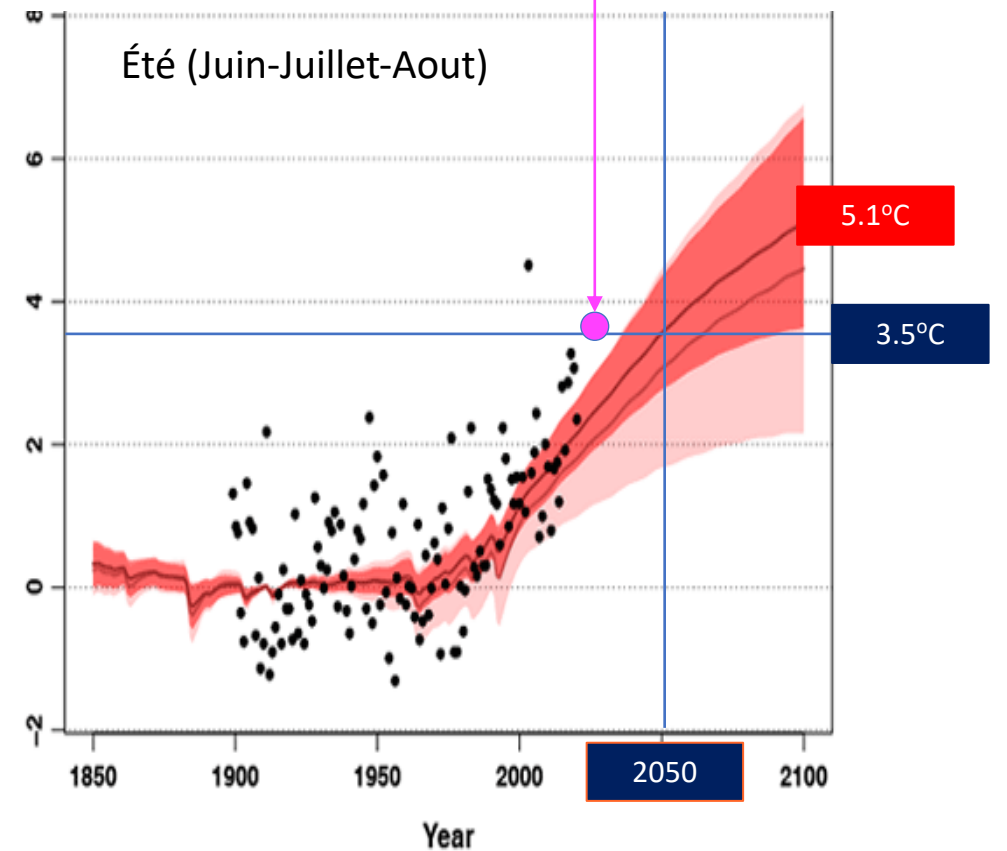
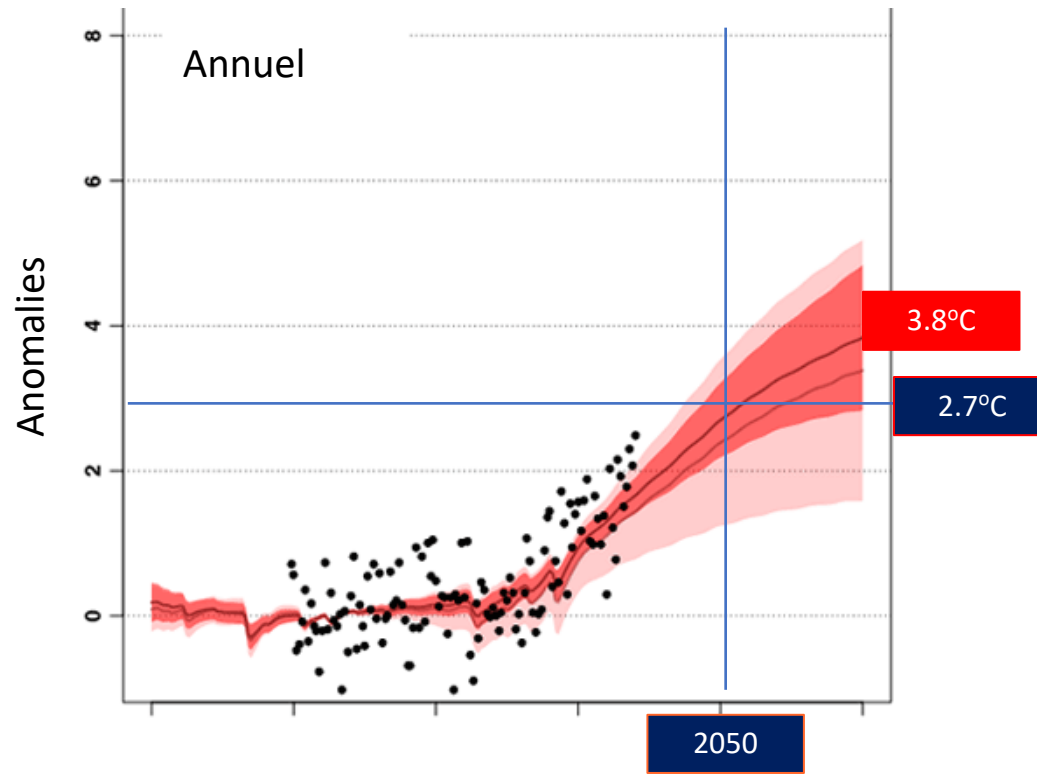
La canicule de juin 2019 : mise en contexte en climat se réchauffant

Probabilité de l'aléa :

- +1.1°C (aujourd'hui) : 1 sur 50
- +1.5°C (avant 2040) : 1 sur 10
- +2°C (vers 2050-60) : 1 sur 4

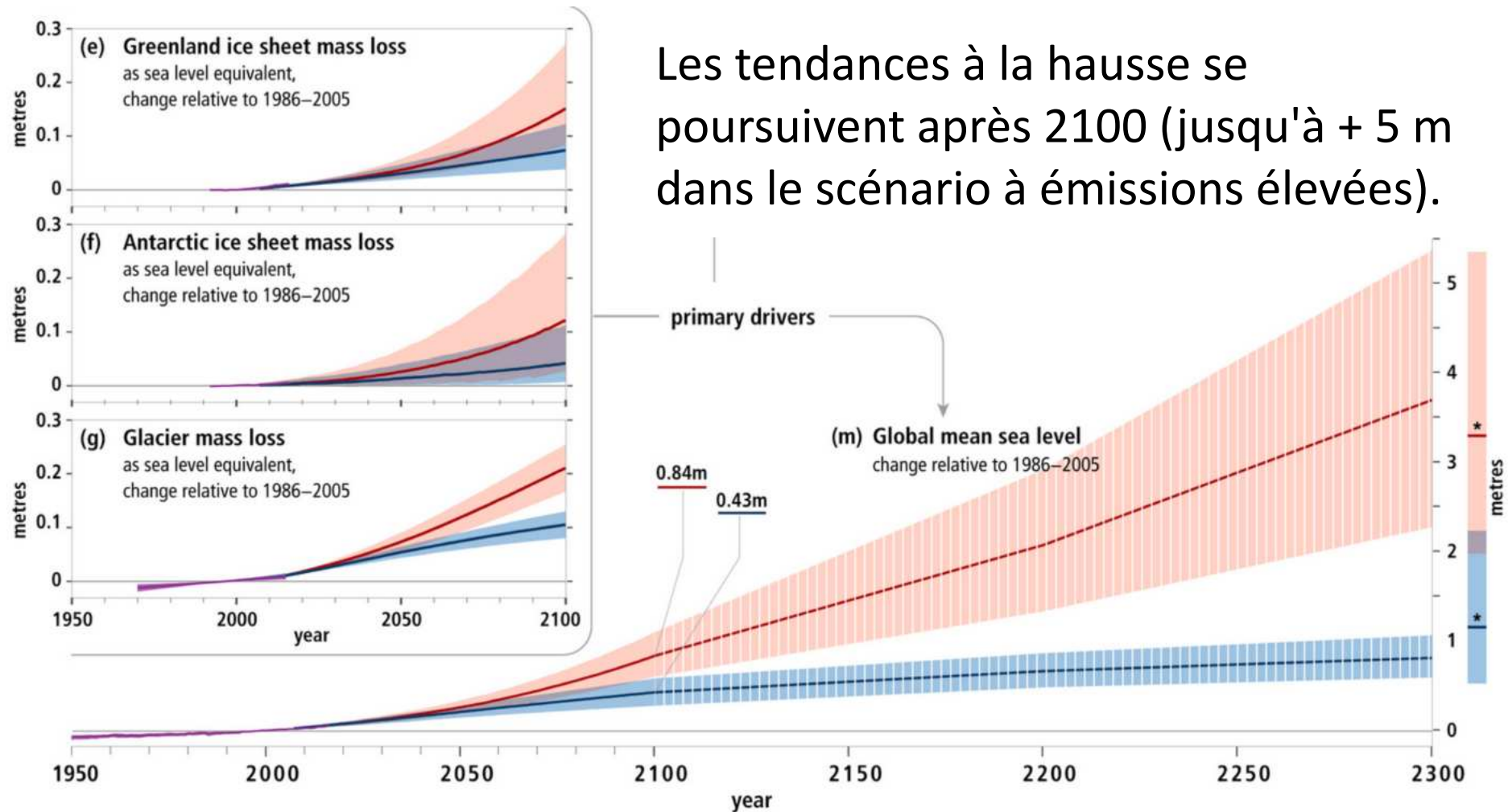
Sur la France, un réchauffement encore plus prononcé

Température sur la France p/r [1900-1930] : scénario tendanciel (~~scénario du laisser-faire~~)

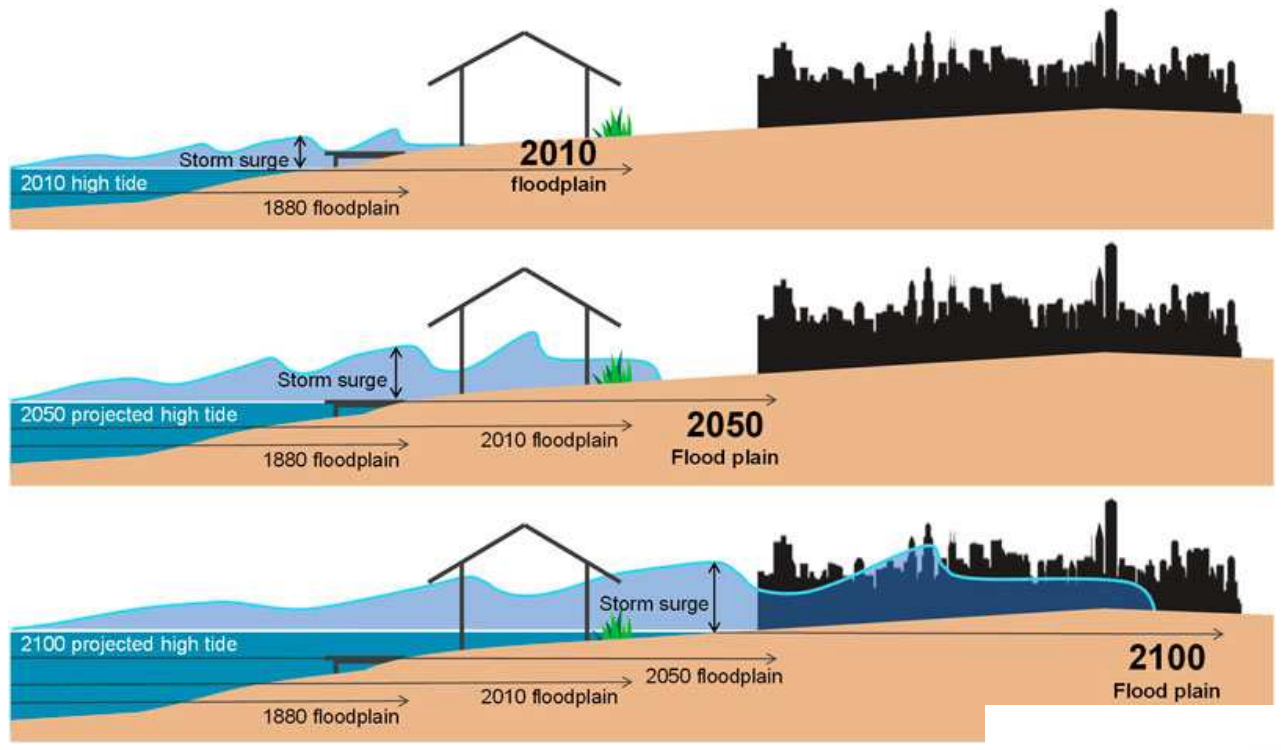


Le niveau des mers – IPCC SROCC 2019

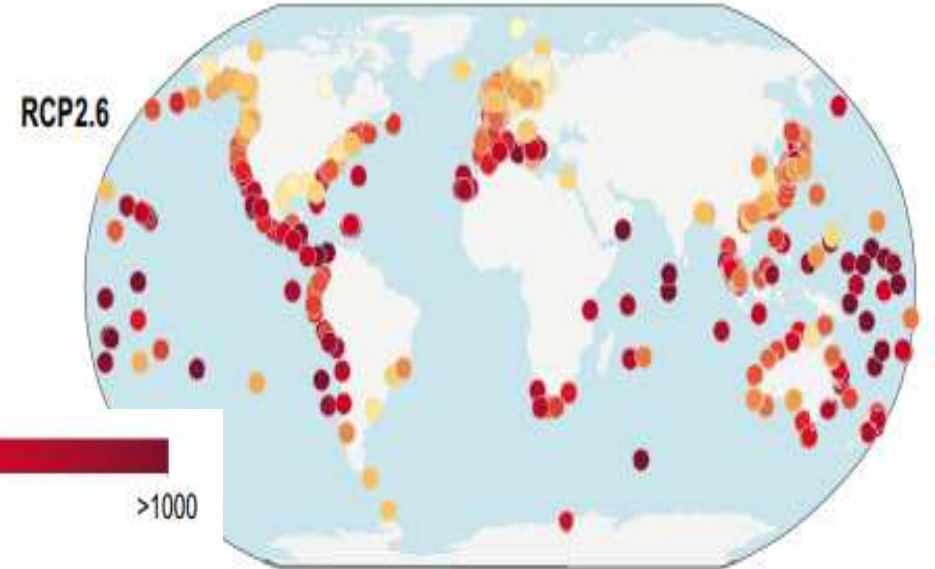
Les projections pour 2100 ont été revues à la hausse (jusqu'à 110 cm pour le scénario à forte émission) - mais plus limitées dans un monde à «2°C».



Les tendances à la hausse se poursuivent après 2100 (jusqu'à + 5 m dans le scénario à émissions élevées).

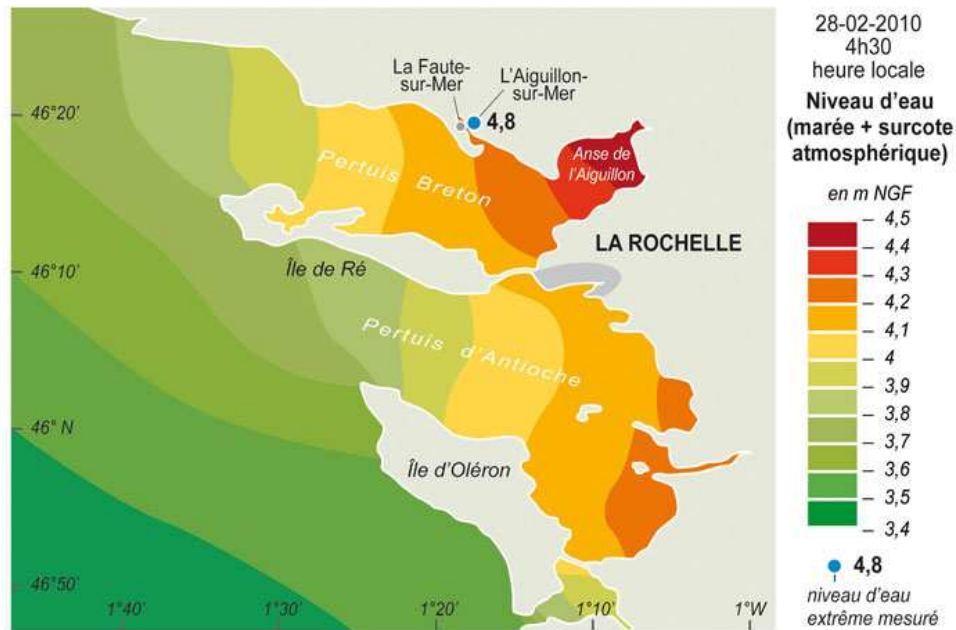


2046-2065





La tempête Xynthia de Fev. 2010 mise en contexte en climat se réchauffant



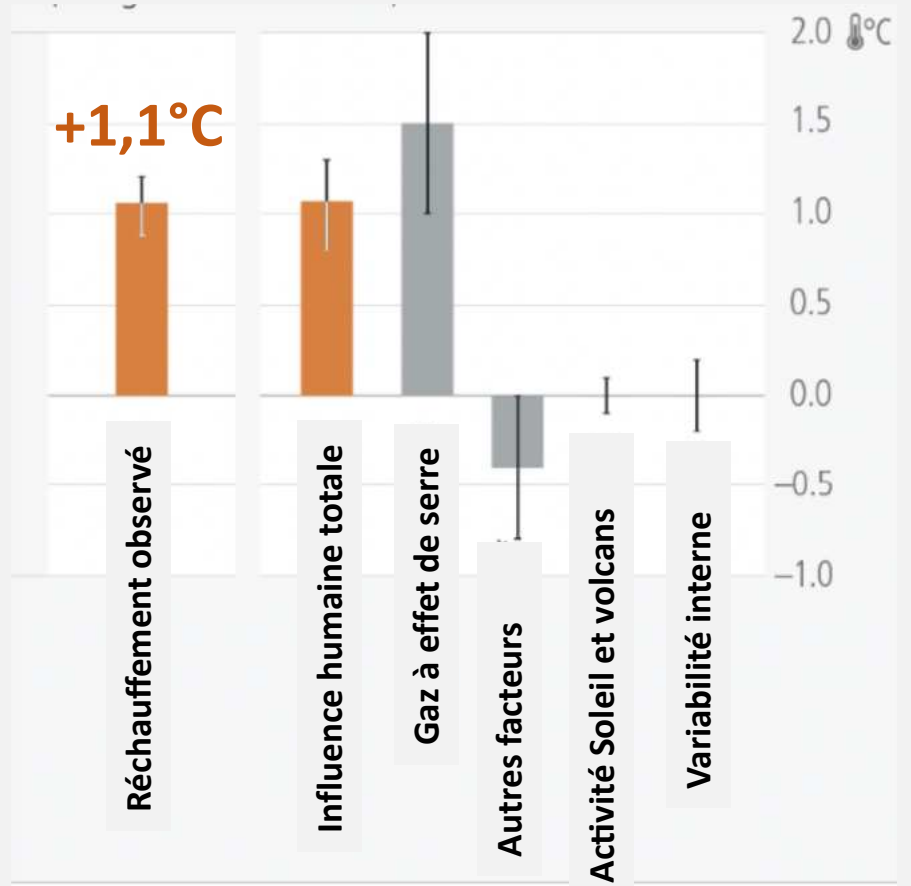
Sources : carte de simulation des niveaux d'eau établie par le BRGM (mars 2010, BRGM/RP-58261-FR, p36.)
niveau d'eau extrême mesuré dans le bourg de l'Aiguillon selon rapport CGEDD (16 sept. 2010, Mission n°007336-01, p21.)

Probabilité de l'aléa :

- +20cm (aujourd'hui) : 1 sur 200
- +50cm (vers 2060) : 1 sur 50
- +1m (2100) : 1 sur 2

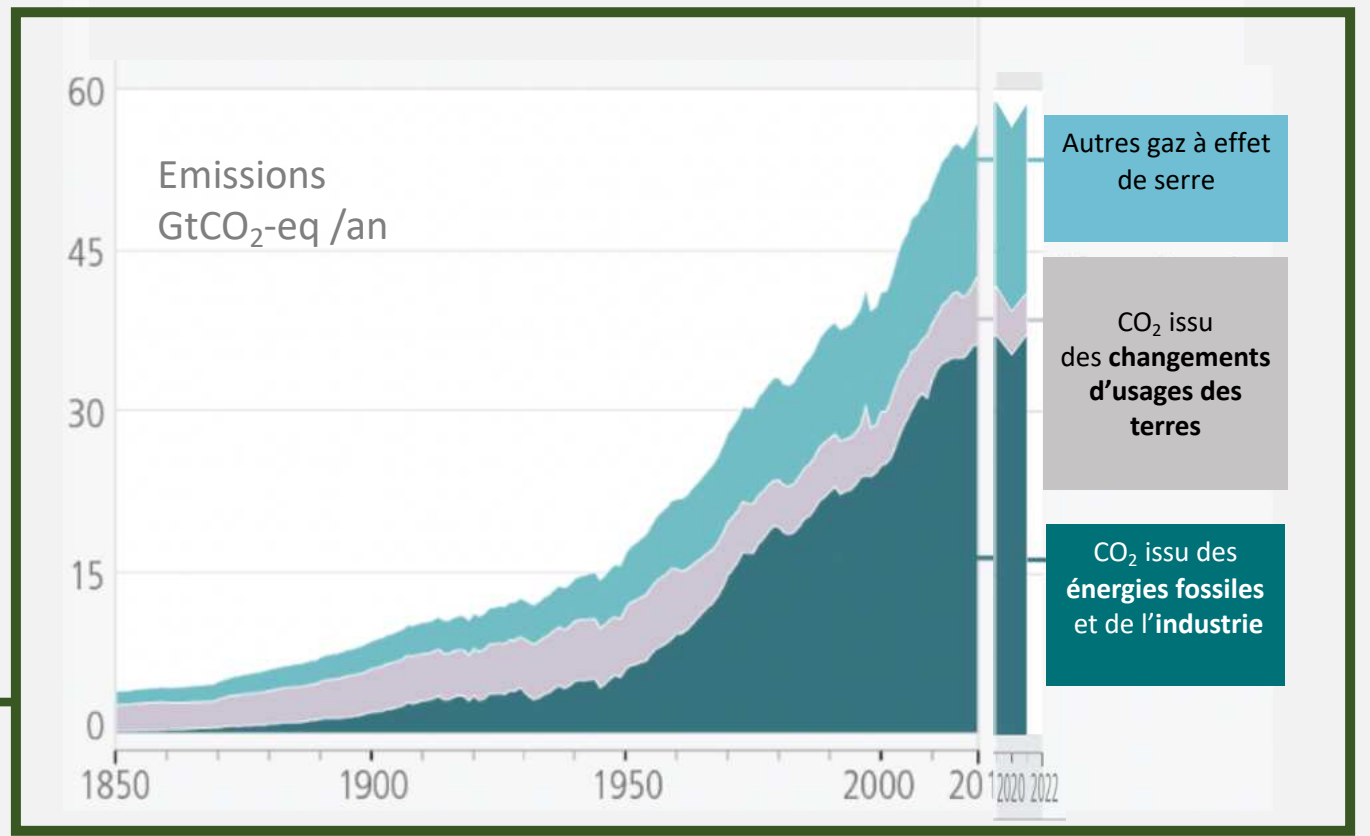
Emissions etc

Les activités humaines sont responsables du réchauffement planétaire



Le réchauffement lié aux émissions de GES est partiellement masqué par le refroidissement dû aux aérosols de pollution

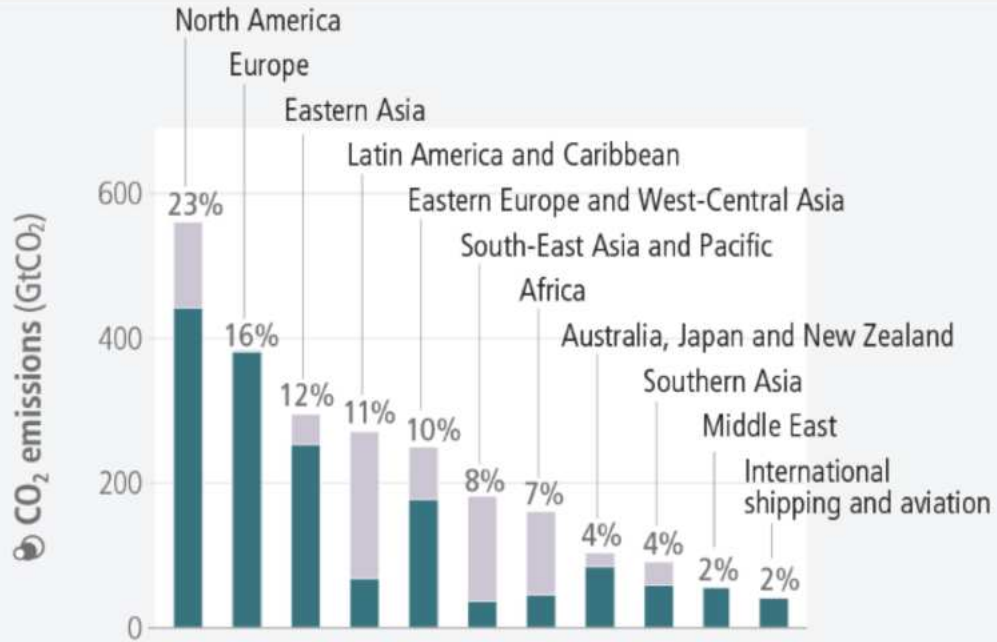
La conséquence de plus d'un siècle de combustion de combustibles fossiles et d'une utilisation inégale et non soutenables de l'énergie et des terres



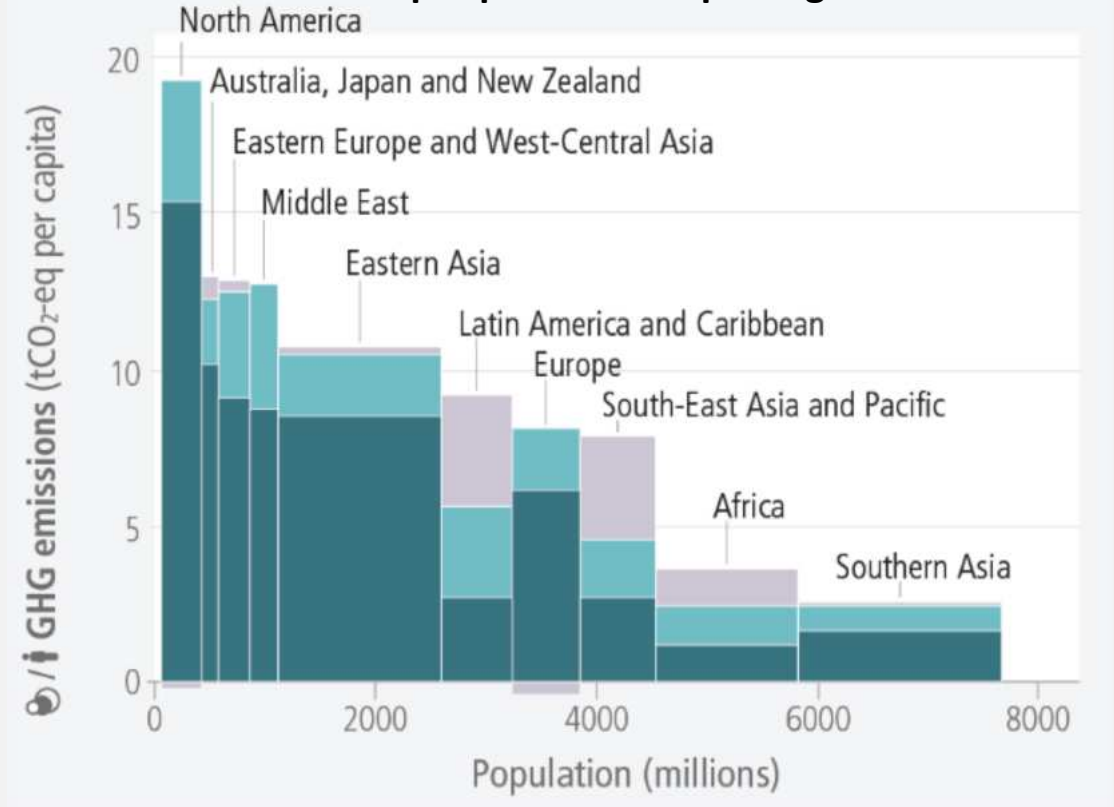
Les émissions de gaz à effet de serre issues des activités humaines continuent d'augmenter

Une distribution inégale des émissions de gaz à effet de serre

Cumul **historique** des émissions nettes de CO₂ par région (1850-2019)



Emissions nettes tous gaz à effet de serre **en 2019** par personne et par région

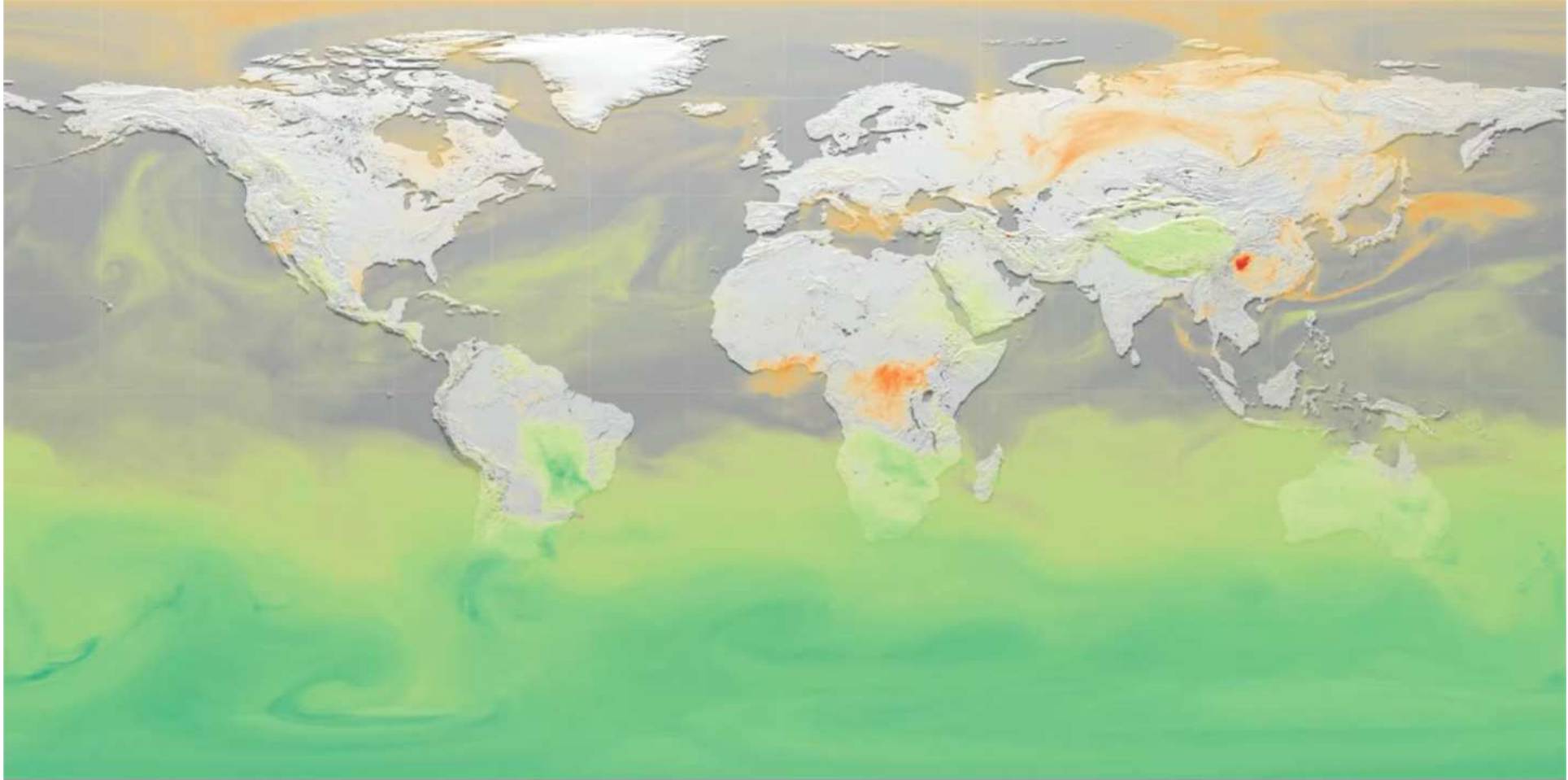


CO₂ issu des **changements d'usages des terres**

Autres gaz à effet de serre

CO₂ issu des **énergies fossiles** et de **l'industrie**

10% des ménages à l'empreinte C la + élevée : ~40% des émissions mondiales
 50% des ménages à l'empreinte C la + faible : ~14% des émissions mondiales



01.01.2015



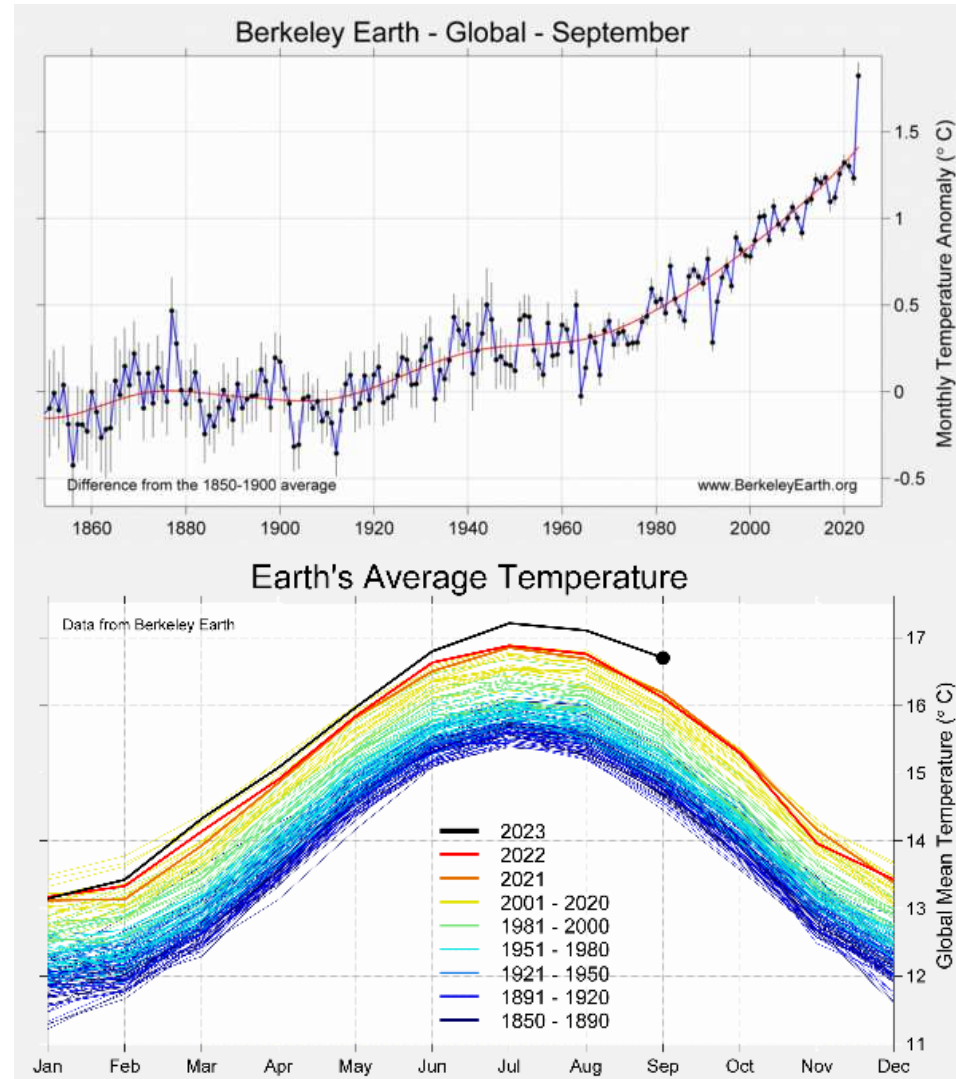
Summer 2023

Bonus (malus)

What happened this summer, and in particular this last september?

This year there has been a stunning increase in global mean temperature.

Multiple factors seem to explain this large increase. The quantitative role of each remains disputed. El niño, high SST, internal variability, aerosol pollution reduction, Honga Tonga eruption

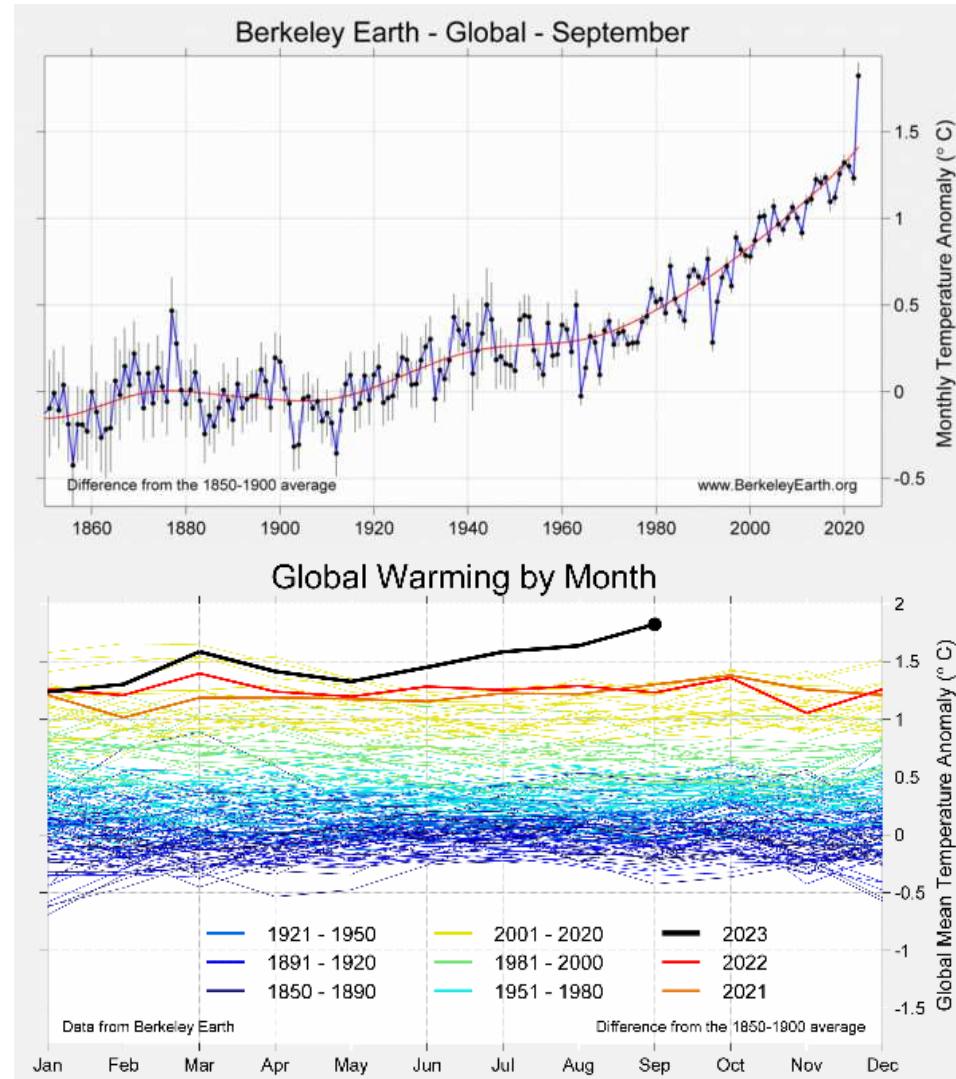


Bonus (malus)

What happened this summer, and in particular this last september?

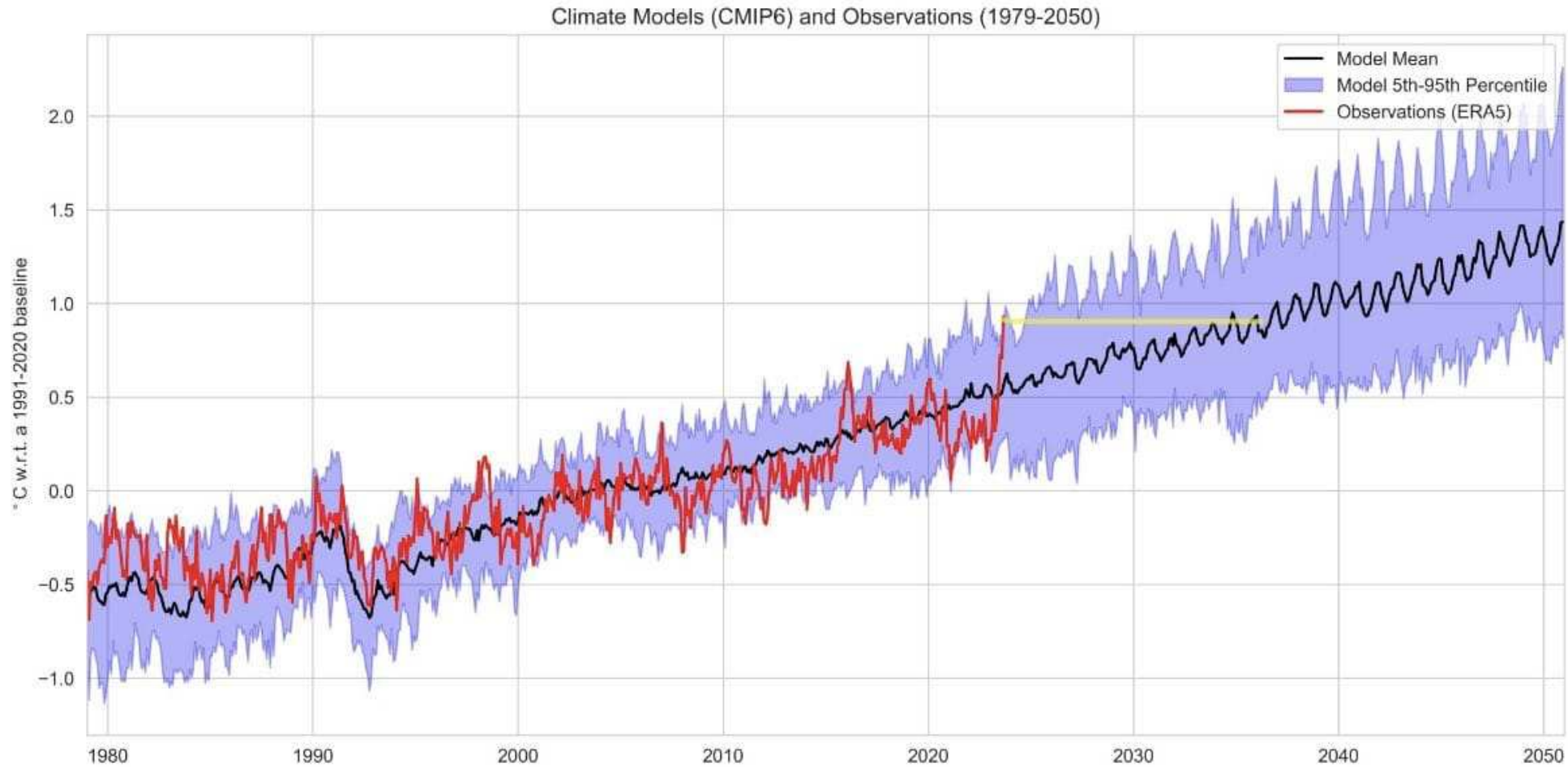
This year there has been a stunning increase in global mean temperature.

Multiple factors seem to explain this large increase. The quantitative role of each remains disputed. El niño, high SST, internal variability, aerosol pollution reduction, Honga Tonga eruption



Is it « out of control », « going bananas », Faster than expected?

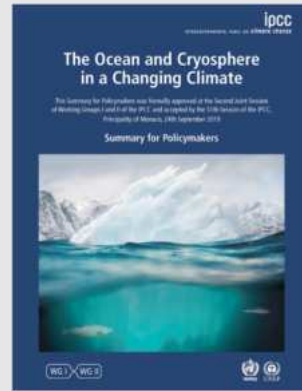
Well, not really. Good news, bad news?



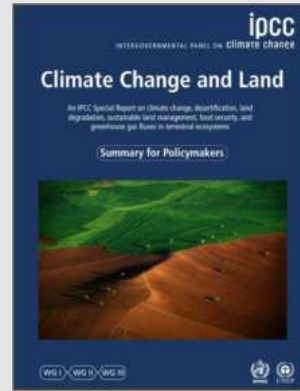
IPCC generic



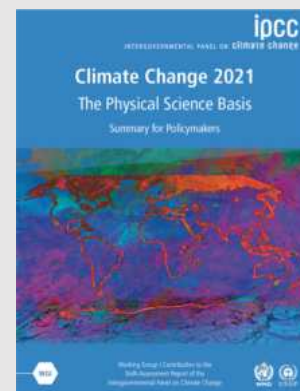
Oct. 2018



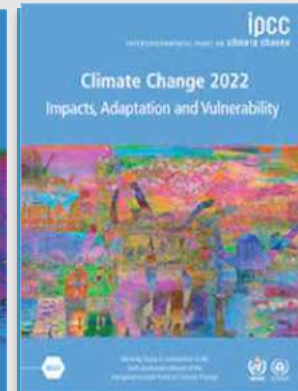
Sept. 2019



Aout 2019



Aout 2021

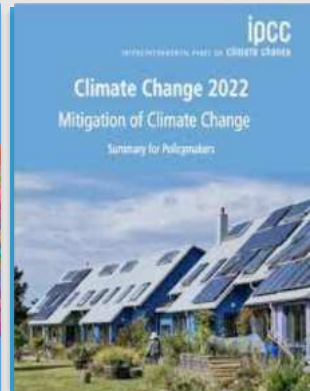
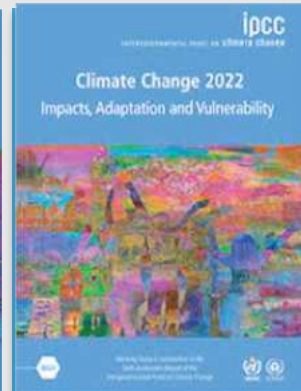
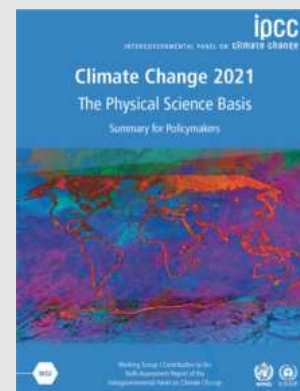
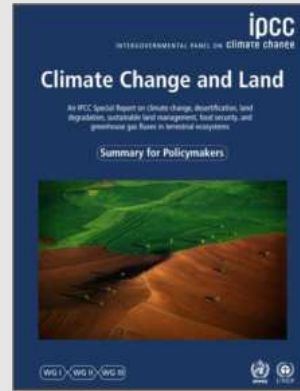
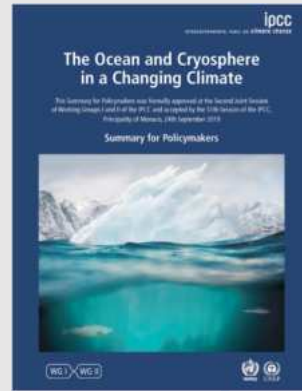


Mars 2022



Avril 2022

Une multitude rapports
entre 2018 et 2022...



Rapport de synthèse

Une multitude rapports entre 2018 et 2022...

... et un rapport de synthèse prévu pour Septembre 2022

Quel est le mandat du GIEC?

Evaluer l'information scientifique, technique et socio-économique pertinente :

- pour comprendre les bases scientifiques des risques du changement climatique dû à l'influence humaine
- ses impacts potentiels
- les options d'adaptation et d'atténuation

Quel est le mandat du GIEC?

Evaluer l'information scientifique, technique et socio-économique pertinente :

- pour comprendre les bases scientifiques des risques du changement climatique dû à l'influence humaine
- ses impacts potentiels
- les options d'adaptation et d'atténuation

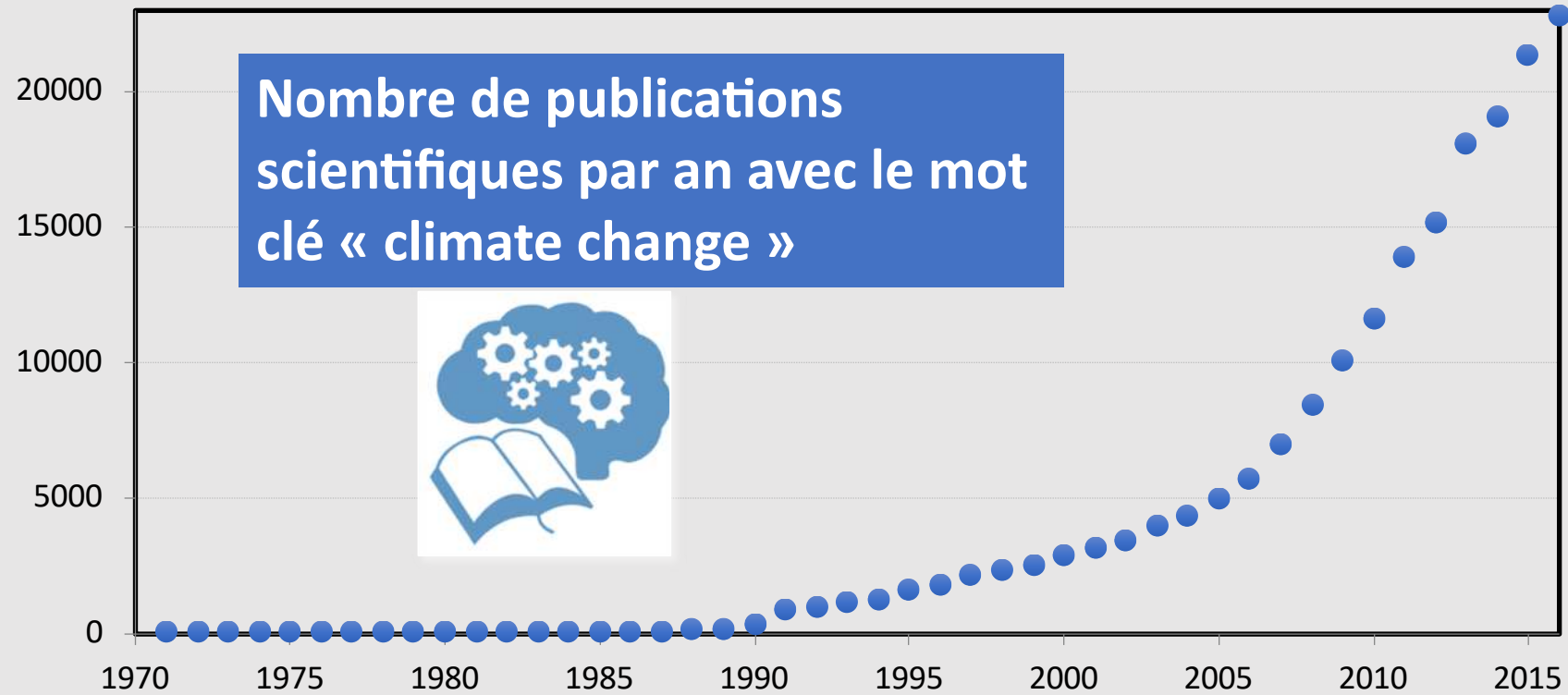
**Une évaluation
pertinente pour éclairer les choix politiques,
neutre, non prescriptive**

Quel est le mandat du GIEC?

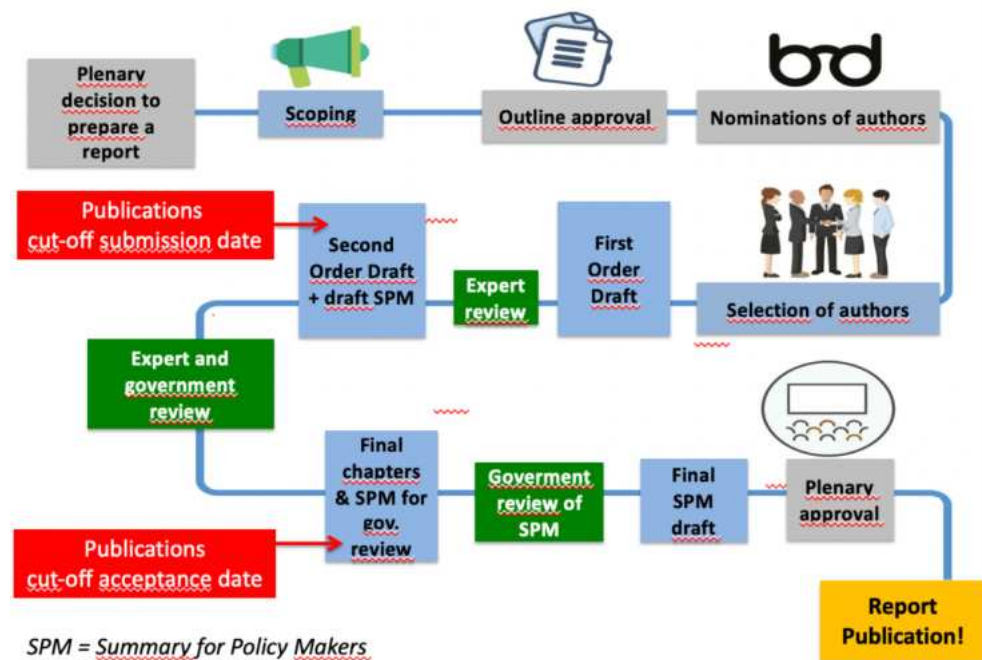
Evaluer l'information scientifique, technique et socio-économique pertinente :

- pour comprendre les bases scientifiques des risques du changement climatique dû à l'influence humaine
- ses impacts potentiels
- les options d'adaptation et d'atténuation

**Le GIEC ne fait pas de recherche
mais stimule la production de connaissances nouvelles et la
maturation des connaissances scientifiques**



Report preparation steps



Chaque rapport est une co-construction

Chaque conclusion issue de l'examen des éléments de connaissances est associée à un degré de confiance

<https://enb.iisd.org/climate/IPCC/IPCC-54-WGI-14>



Auteurs

234 scientifiques de **65** pays
28% femmes, **72%** hommes
63% nouveaux auteurs



Éléments probants de 14,000
publications scientifiques examinés



Processus de relecture

78,000+ commentaires
1890 experts relecteurs de **92** pays
46 gouvernements sur la dernière version



1^{ère} approbation virtuelle

186 heures zoom

“



[Credit: NASA]

L'influence humaine sur le climat est sans équivoque

ipcc

INTERGOVERNMENTAL PANEL ON climate change



WMO



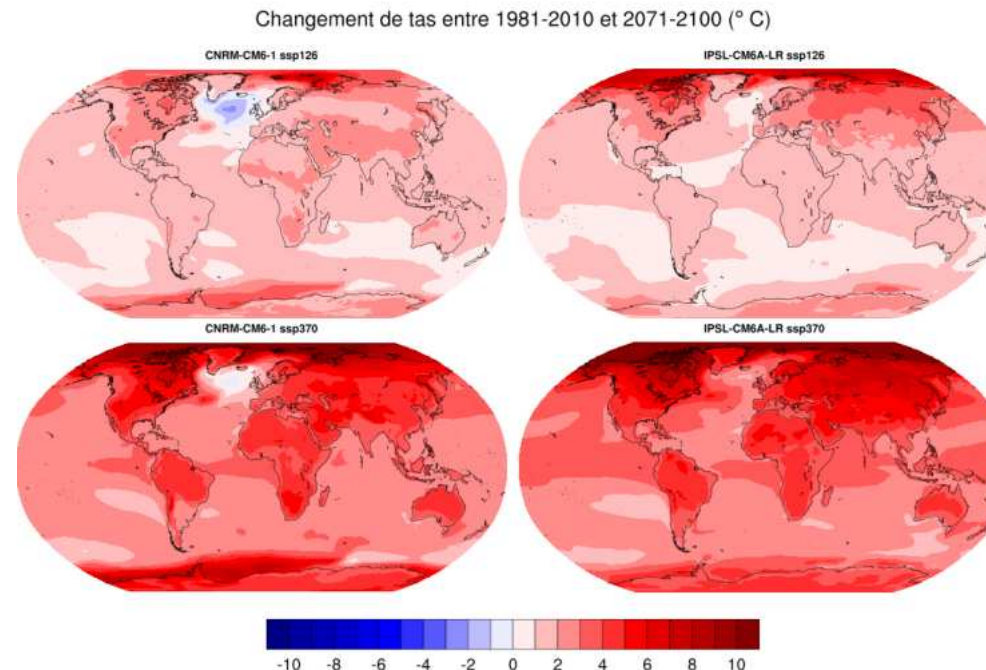
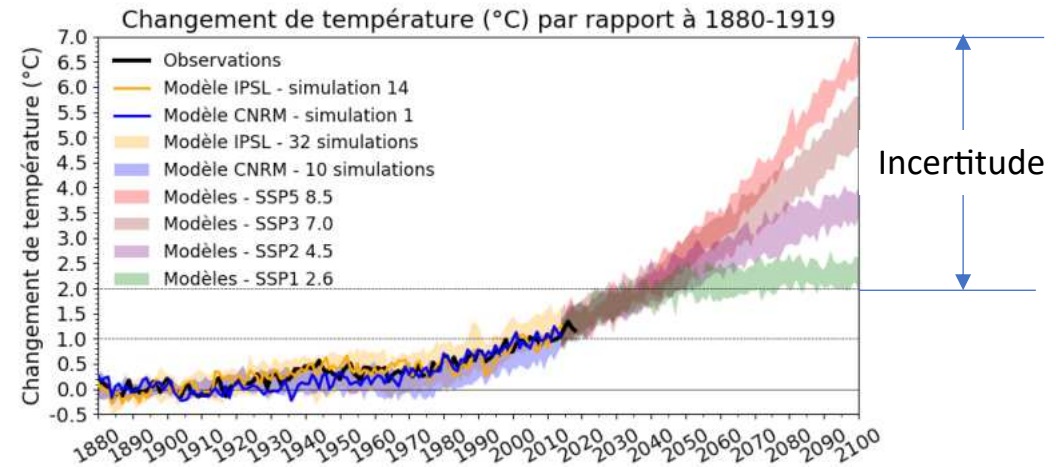
UNEP

Résultats

Mais:

Le système climatique n'est pas à l'équilibre. Et l'incertitude sur la hausse de température n'a pas diminué depuis le début des estimations dans les années 80-90.

Une conséquence encore de la non-linéarité du climat.



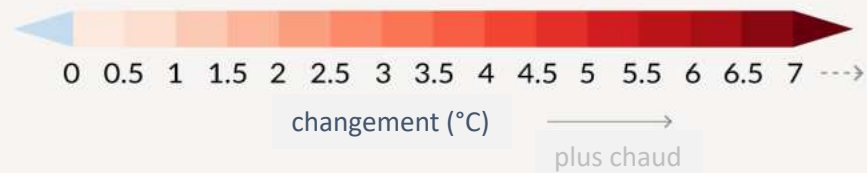
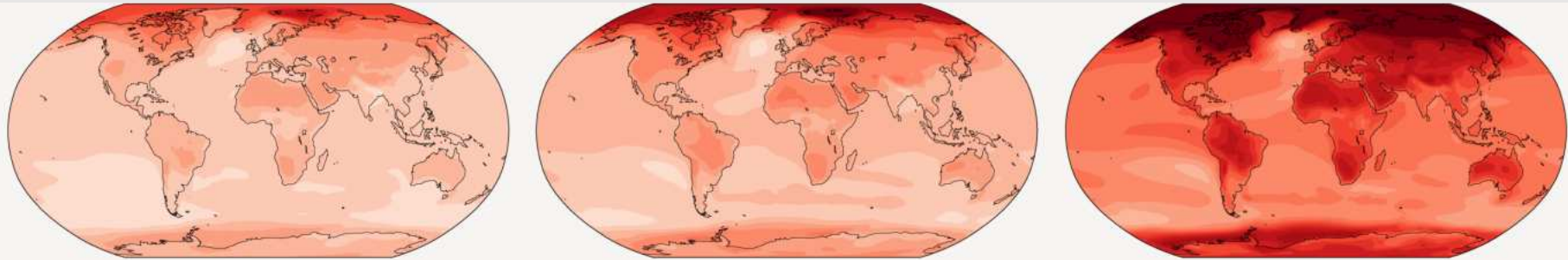
**Pour chaque fraction de réchauffement planétaire supplémentaire,
les changements sont amplifiés dans chaque région**

Changements de température moyenne annuelle ...

... pour 1,5°C

... pour 2°C

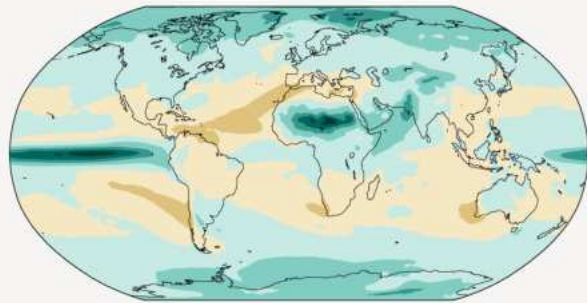
... pour 4°C



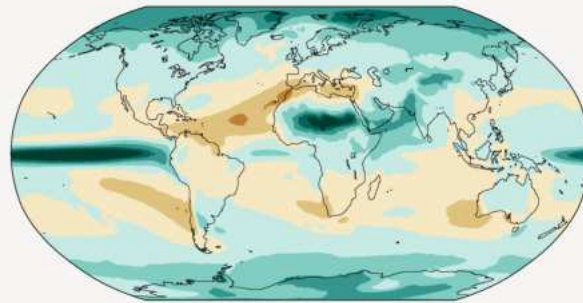
Pour chaque fraction de réchauffement planétaire supplémentaire, les changements sont amplifiés dans chaque région

Changements de précipitations en moyenne annuelle ...

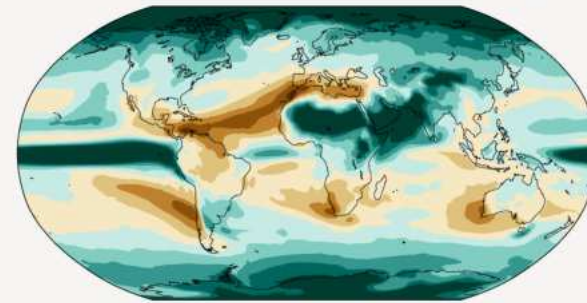
... pour 1,5°C



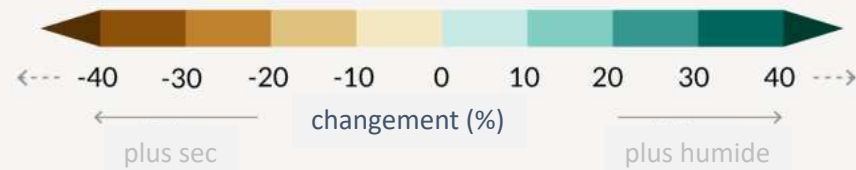
... pour 2°C



... pour 4°C



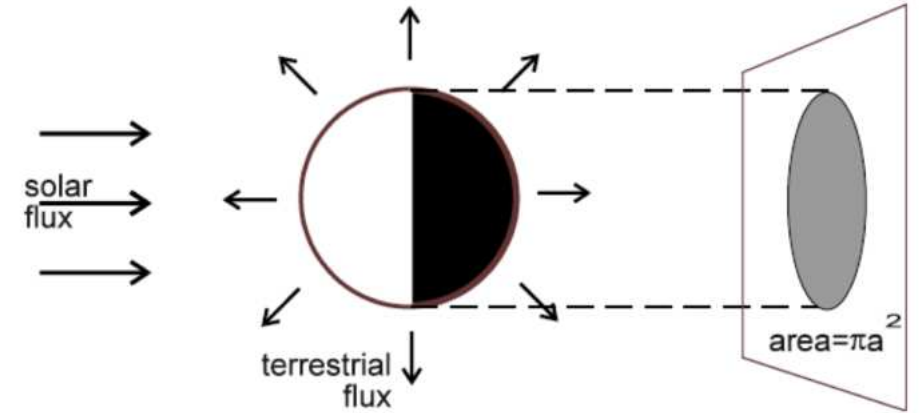
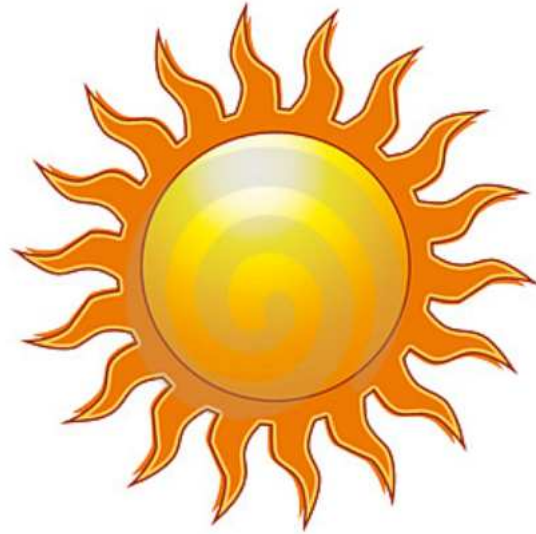
Certains changements sont faibles en valeur absolue mais apparaissent larges en % dans les régions sèches



GH effect Radiation



The radiative balance of planet Earth

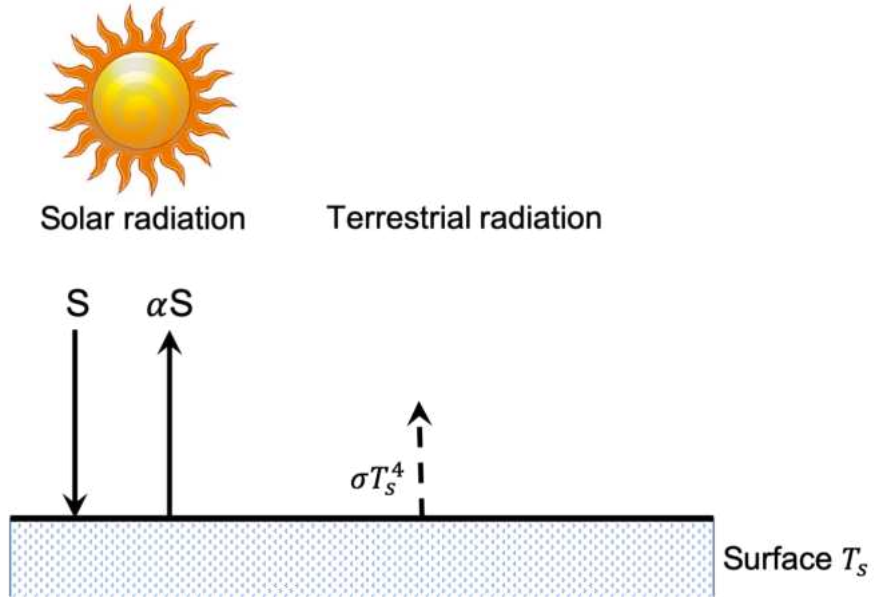


The planet is a **blackbody**

Stephan-Boltzmann law: $W = \sigma T^4$



The radiative balance of planet Earth



Let's compute something,
to stretch our legs...

$$S(1 - \alpha) = \sigma T_s^4$$

$$T_s = \left[\frac{S(1 - \alpha)}{\sigma} \right]^{\frac{1}{4}} = 255 \text{ } ^\circ K = -18^\circ C$$

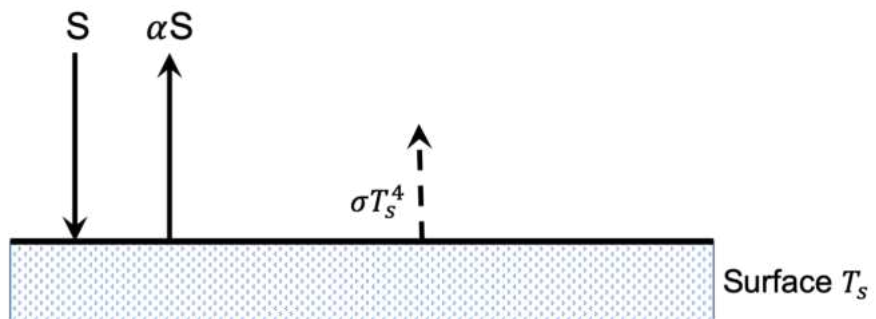


The radiative balance of planet Earth



Solar radiation

Terrestrial radiation



Let's compute something, to stretch our legs...

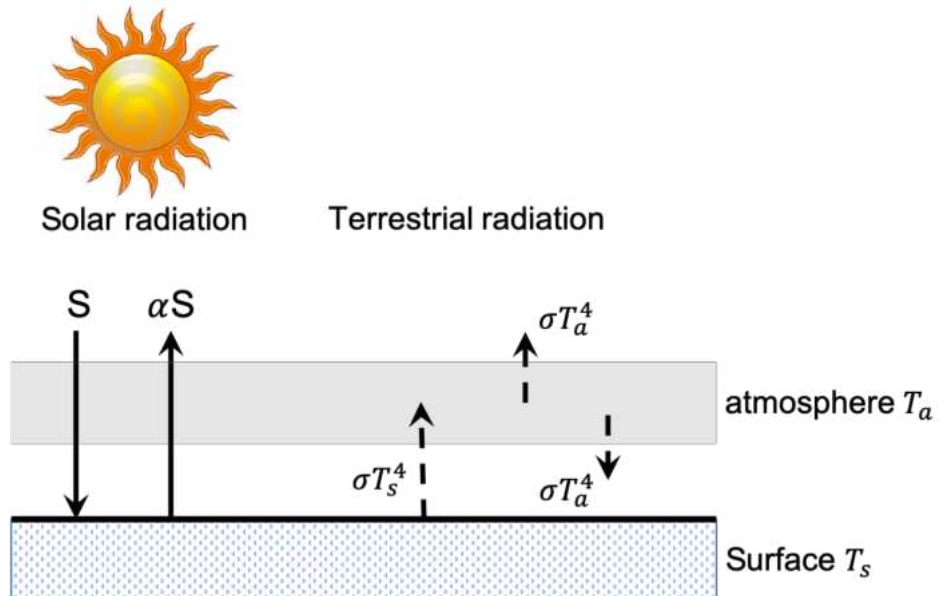
$$S(1 - \alpha) = \sigma T_s^4$$

$$T_s = \left[\frac{S(1-\alpha)}{\sigma} \right]^{\frac{1}{4}} = 255 \text{ } ^\circ K = -18^\circ$$

Too Cold



The radiative balance of planet Earth



Radiative balance at the top of the atmosphere

$$\frac{S_0}{4}(1 - \alpha) = \sigma T_a^4$$

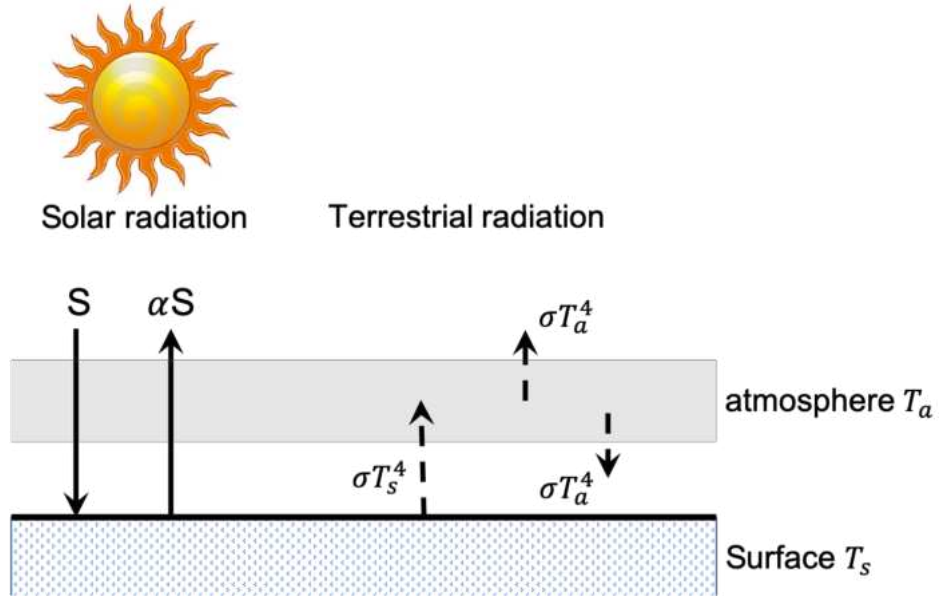
Radiative balance at the surface of the Earth

$$\frac{S_0}{4}(1 - \alpha) + \sigma T_a^4 = \sigma T_s^4$$

hence
$$T_s^4 = 2 \frac{S_0}{4}(1 - \alpha) \Rightarrow T_s = 2^{\frac{1}{4}} 255 \text{ K} = 303 \text{ K}$$



The radiative balance of planet Earth



Radiative balance at the top of the atmosphere

$$\frac{S_0}{4}(1 - \alpha) = \sigma T_a^4$$

Radiative balance at the surface of the Earth

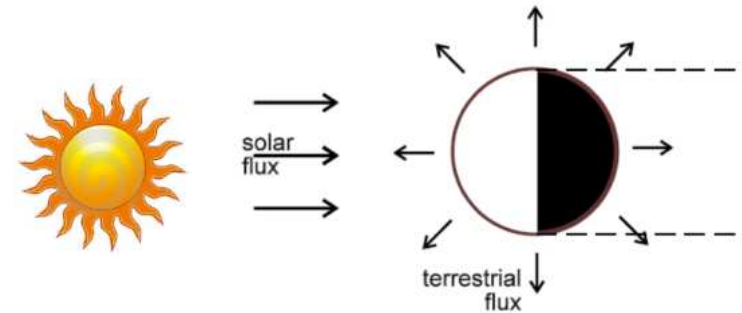
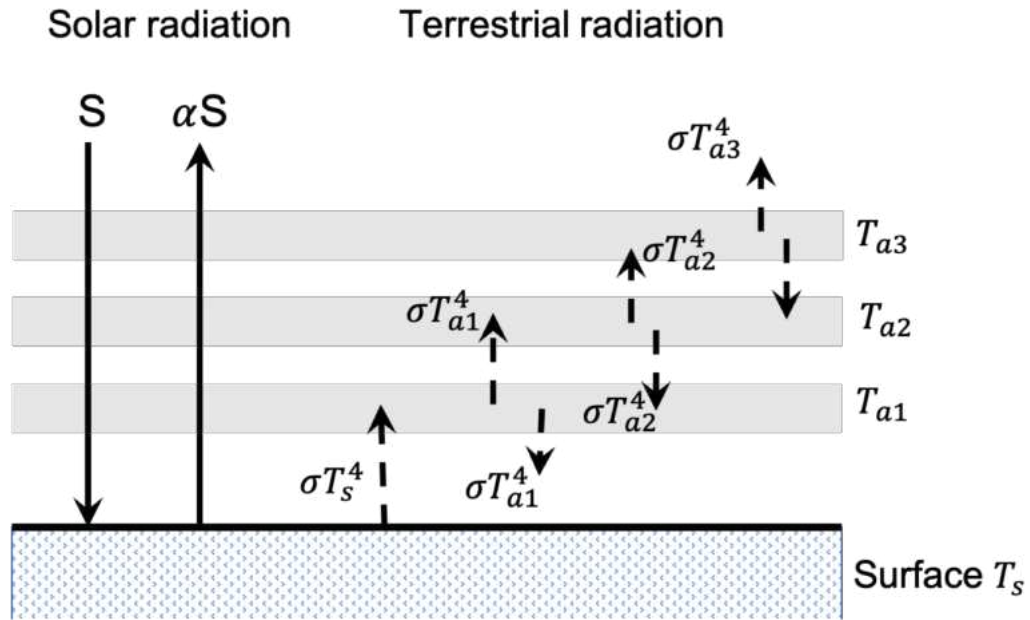
$$\frac{S_0}{4}(1 - \alpha) + \sigma T_a^4 = \sigma T_s^4$$

hence $T_s^4 = 2 \frac{S_0}{4}(1 - \alpha) \Rightarrow T_s = 2^{\frac{1}{4}} 255 \text{ K} = 303 \text{ K}$

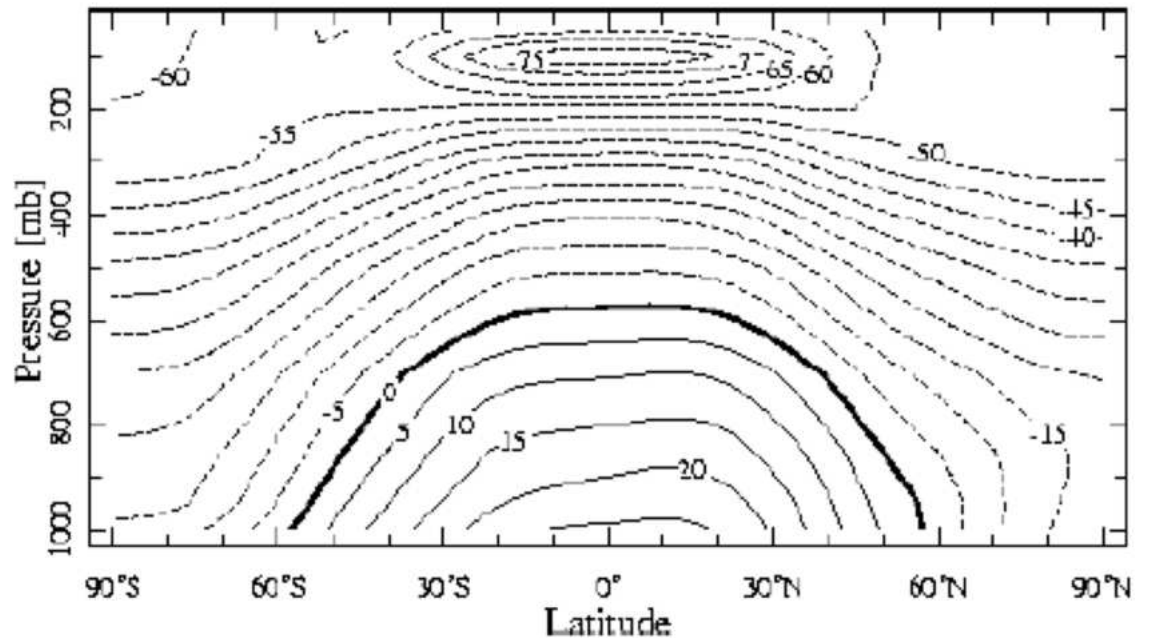
**Too Hot
(a little)**



The radiative balance of planet Earth



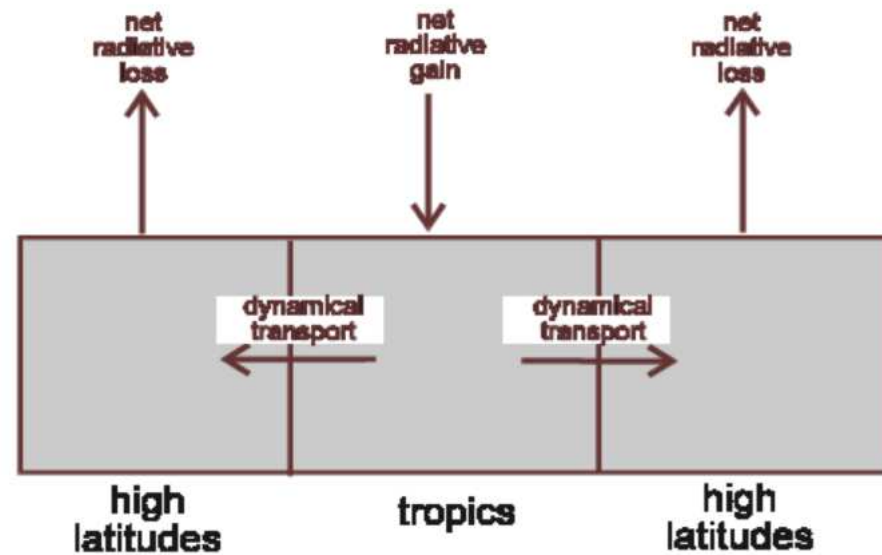
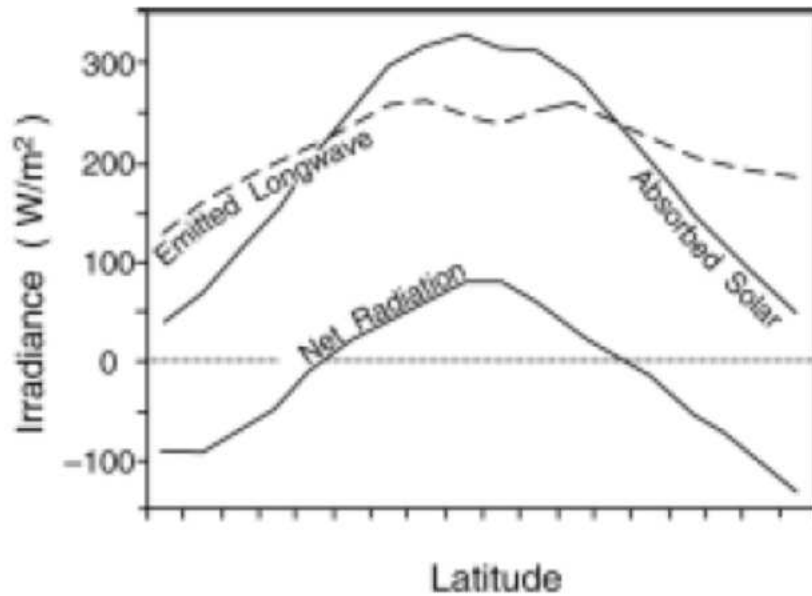
Latitudinal and vertical structure of the atmosphere





The radiative balance of planet Earth

The thermal engine of Earth fluid motion : The dynamics of the atmosphere and the ocean



GCMs,
dynamics
Parametrizations

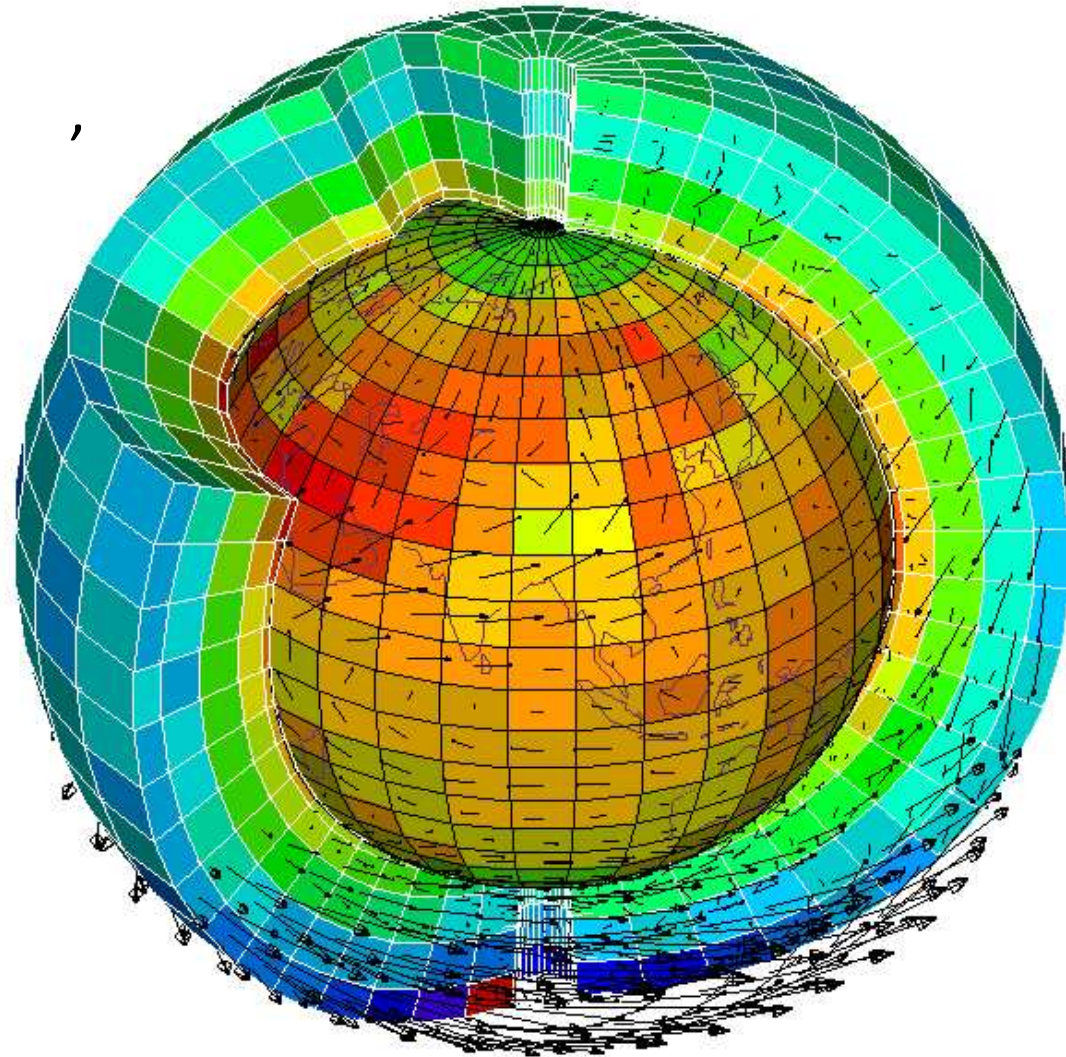
...Au plus compliqué: modèles de circulation générale

« briques » de 100 km x 1 km

1 valeur de P, T, \vec{v} ,

et composition moyenne
(vapeur d'eau...)

➤ État de l'atmosphère
instantané



Évolution : « Cœur dynamique » -- équations primitives

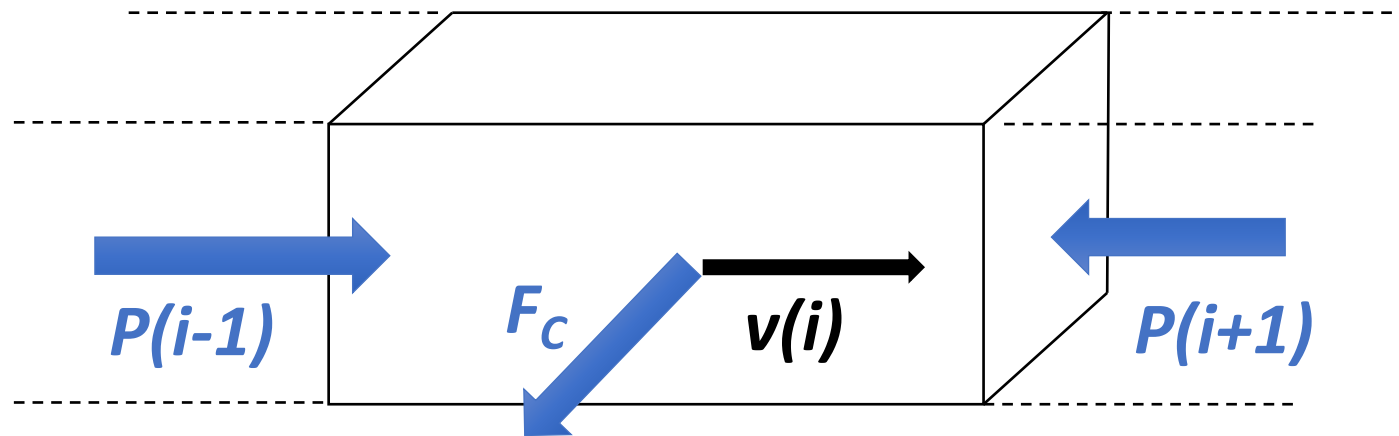
- Mouvement horizontal: $\frac{d\vec{v}}{dt} + f \vec{k} \wedge \vec{v} = -1/\rho \nabla p$
- Équilibre hydrostatique: $\frac{\partial p}{\partial z} = -\rho g$
- Conservation de la masse: $\frac{\partial \rho}{\partial t} + \text{div}(\rho \vec{v}) = 0$
- Équation d'état (gaz parfaits) $\frac{p}{\rho} = R_a T$
- Conservation de l'énergie $c_p \frac{dT}{dt} - \frac{1}{\rho} \frac{dp}{dt} = q$

Méthode : différences finies

$$\frac{d\vec{v}}{dt} + f \vec{k} \wedge \vec{v} = -1/\rho \nabla p$$

Accélération Coriolis

Force pression

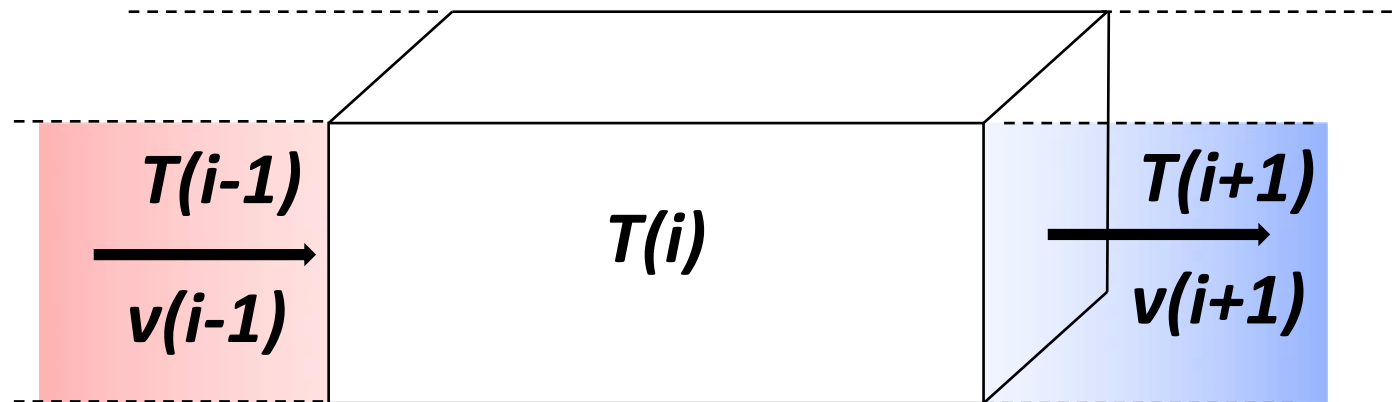


Calcul tous les pas de temps de quelques secondes

Advection de température (ou humidité...)

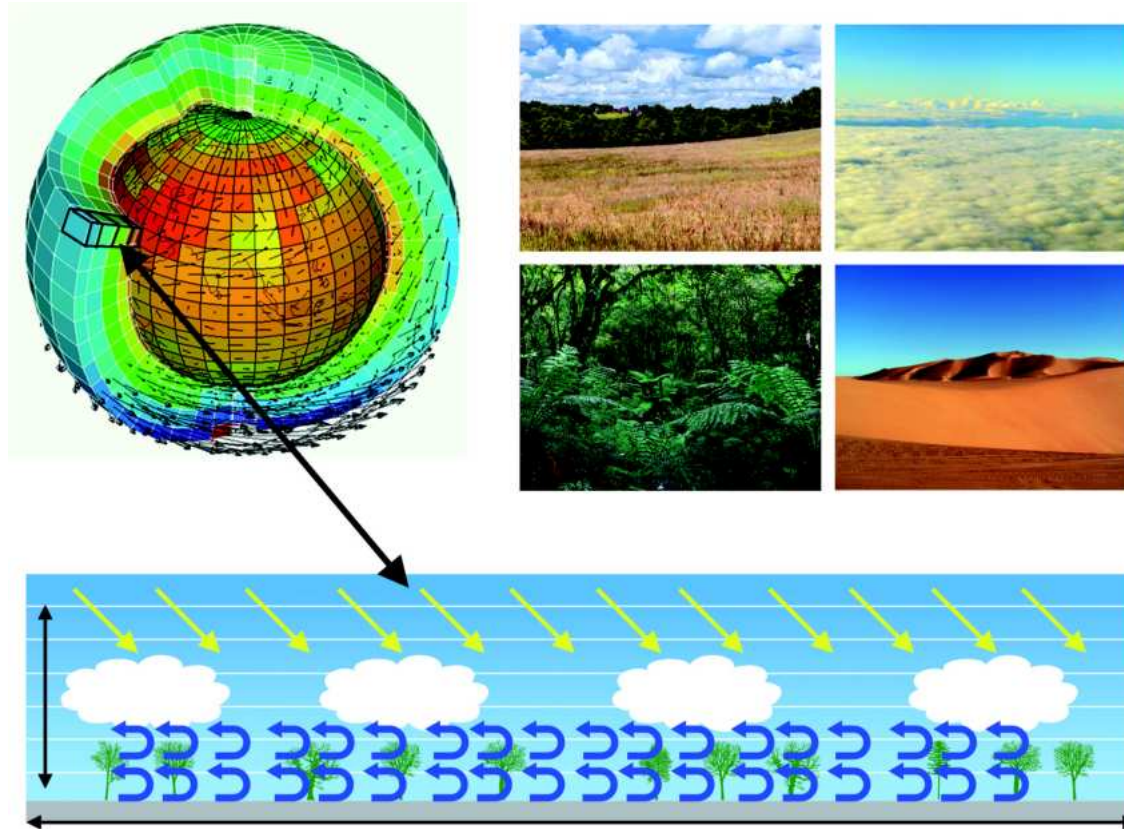
$$\frac{\partial T}{\partial t} = -\vec{v} \cdot \overrightarrow{\text{grad}} T + \dots$$

Évolution de T : transport par le vent



Calcul tous les pas de temps de quelques secondes

2) Un exemple: les parameterization physiques des modèles de climat

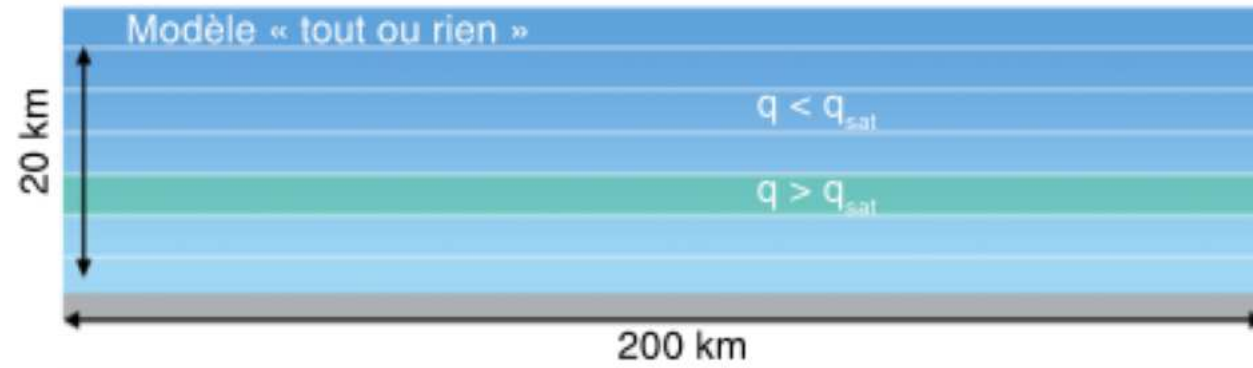


Impact des processus sous-maille sur sur les valeurs moyennes de la maille
La statistique entre en jeu.

Exemple: formation de nuages

On connaît: les valeurs moyennes pour chaque maille de :
température \bar{T} , humidité \bar{q} .

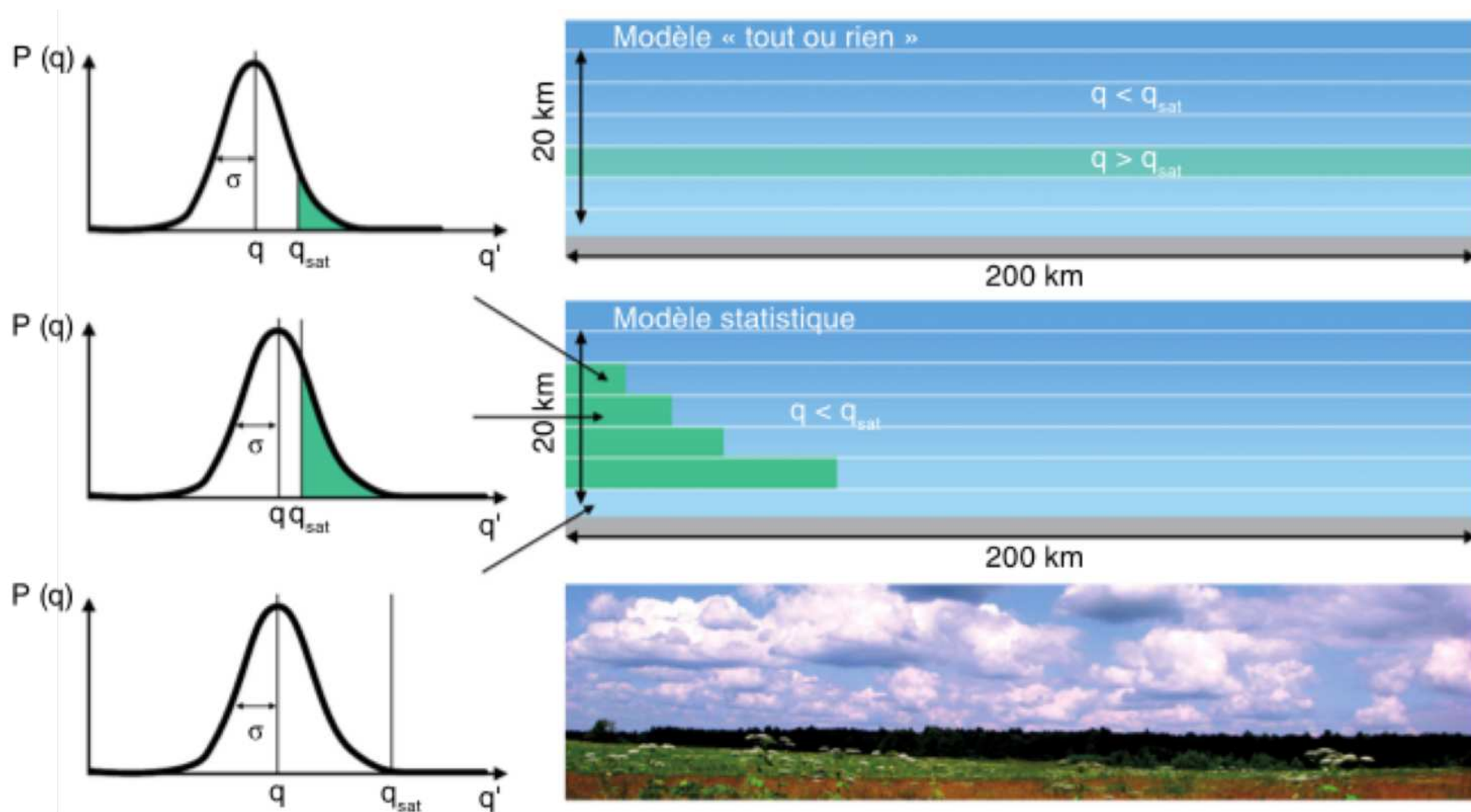
1. Hypothèse de base : condensation si $\bar{q} > q_{sat}(\bar{T})$



...Mais les nuages ressemblent plutôt à ça :



➤ Hypothèse 2: distribution sous-maille de l'humidité autour de \bar{q}
Condensation de la fraction qui dépasse $q_{sat}(\bar{T})$

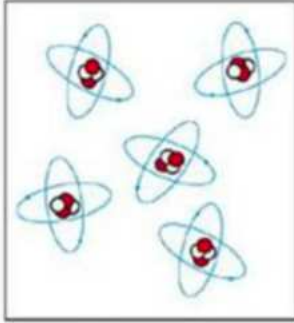

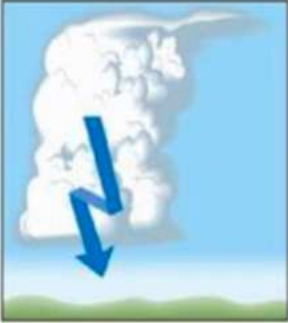




Different hypotheses possibles sur la PDF:

- Uniform or Log-normal
- constant or varying sigma

Ou des choses plus complexes:

- bi-normale ou multinormale
- Couplage avec des schémas de convection profonde ou peu profonde, et/ou de turbulence

Name:	Molecular	Micro	Meso	Synoptic	Global
Examples:					
Size range:	Microscopic or smaller	Millimeters to a few kilometers	2–2000 kilometers	1000–5000 kilometers	2500–25,000 kilometers
Typical duration:	Microseconds, milliseconds	1 second to minutes	Minutes to hours	Days	Weeks or longer
Examples	heat conduction molecular dispersion	wind gusts rain drops	thunderstorms fronts	cyclones air masses	ITCZ, SPCZ El Niño

Error growth $t_3 = \text{minutes}$... $t_2 = 1 \text{ days}$ $t_1 = 5 \text{ days}$

$$\sum_{i=1}^N t_i \rightarrow \tilde{T} \text{ pour } N \rightarrow \infty \quad \text{Limite théorique à la prévisibilité}$$

C'est dans la nature de l'atmosphère, de ne pas être prévisible.

Est que c'est vrai? C'est lié à un des « millennium mathematical problems! »