Lecture 1 : climate

Main goals:
a science / society topic for physicist
develop a **curiosity and interest** for other sciences : interdisciplinary sciences
hands on : choose a question and study it by bibliographic, modeling and experimental means

rules :
I'll be a guide, not an expert (eventually no one is expert over all topics we are going to tackle). We will face questions on which I will have no answer => choose it for your project and share your answer or wait for me to look for the answer in the next weeks.
In the end, allmost all scientific questions have an answer in IPCC reports.

English : if you don't understand some word, ask me in French, if I can't find my word in Englis, I'll turn to French

Scope

Climates

Radiative balance and greenhouse effect

Energy redistribution and global circulation

Main cycles and anthropic perturbations

Climate modelling and predictions

Probe of global warming and impacts

Main references :

Atmosphere, océan et climat, *Delmas, Chauzy, Verstraete, Ferré* (Belin)
Climat, passé, présent et futur, *Mélières, Marechal* (Belin)
Le climat à découvert, *Jeandel, Mosseri* (CNRS éditions)
Global warming, understanding the forecast, *Archer* (Wiley)
Introduction aux sciences de l'atmosphère, *Spiga* (poly UPMC)
Sciences et sociétés, Chapitre 3, *Blanc* (poly UPMC)
IPCC reports

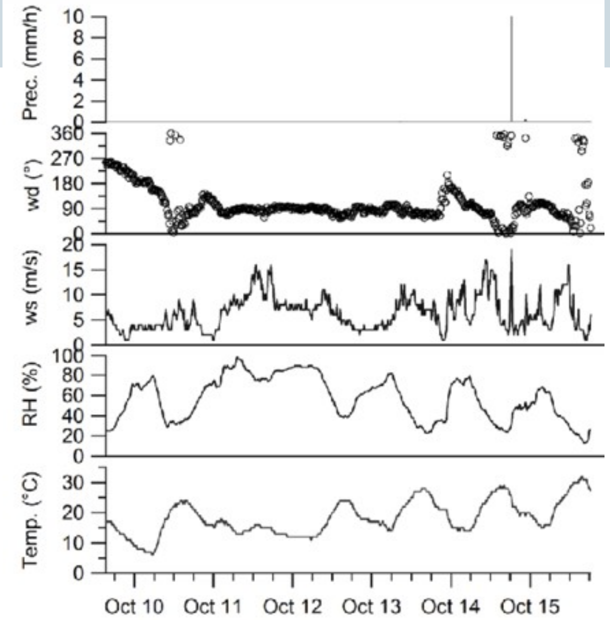
Climates

Climate vs weather forecast

- Typical parameters for weather forecast : temperature, pressure, wind speed/direction, humidity, rainfall, sunlight

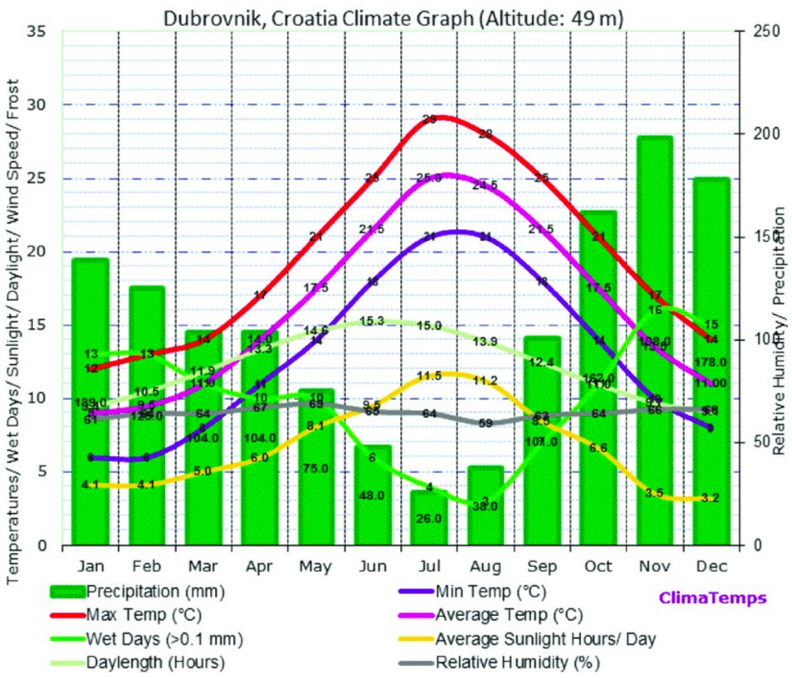
  => the goal is to predict with a good accuracy in space and time the weather the near future (~ one week)

  in terms of statistics : single trajectory (event)



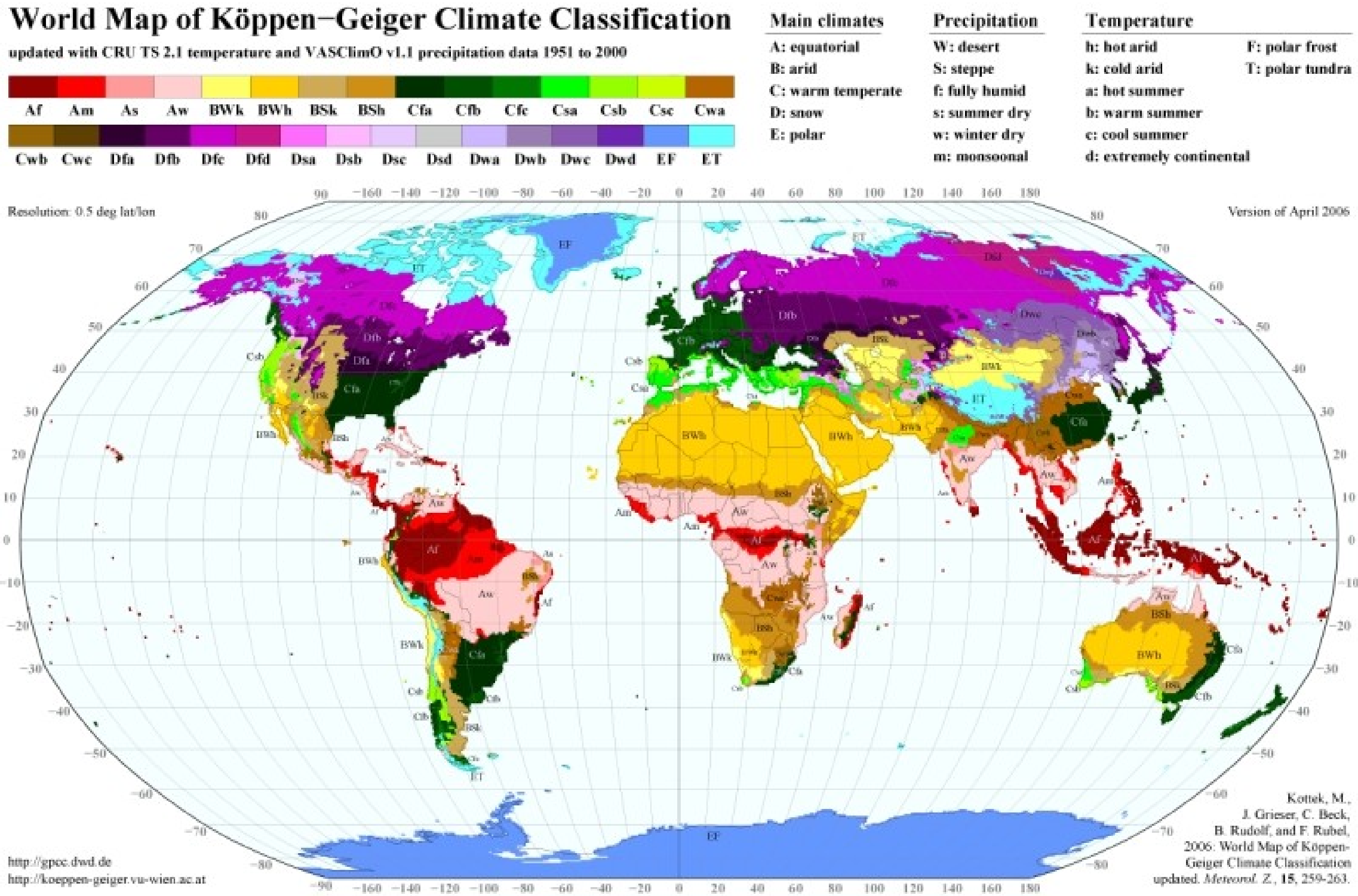
Typical parameters for climate : temperature (average, min/max), rainfall, sunlight

=> the goal is to provide typical living conditions
in terms of statistics :
many trajectories (events)
to get average and fluctuations.
Time-scale => a few decades



Climate distribution across the world

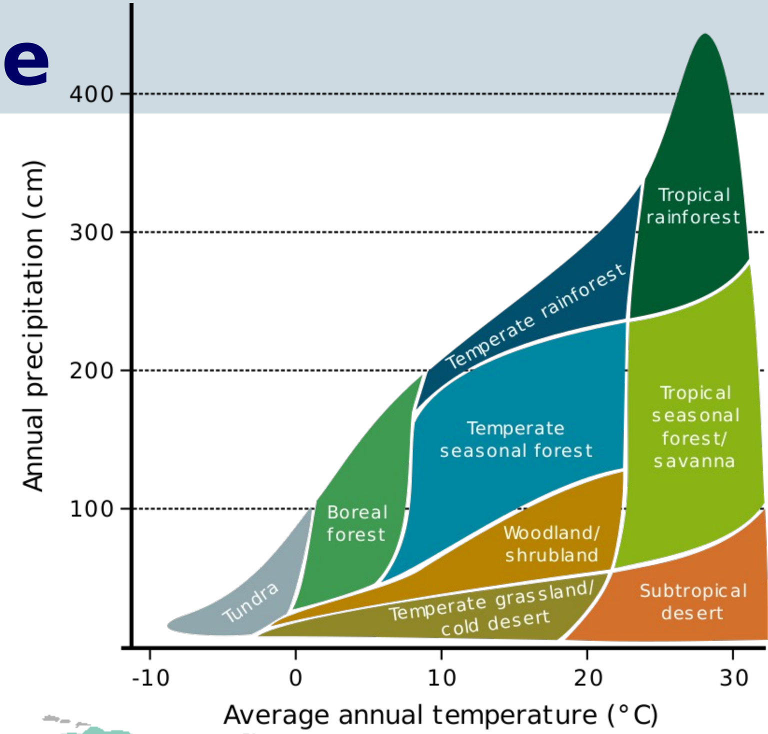
- The goal of climatology is to provide scientifical answers to the observations of these various climates, their fluctuations, their history and their evolution. It is naturally an interdisciplinary science (physics, chemistry, geology, biology, applied mathematics...)

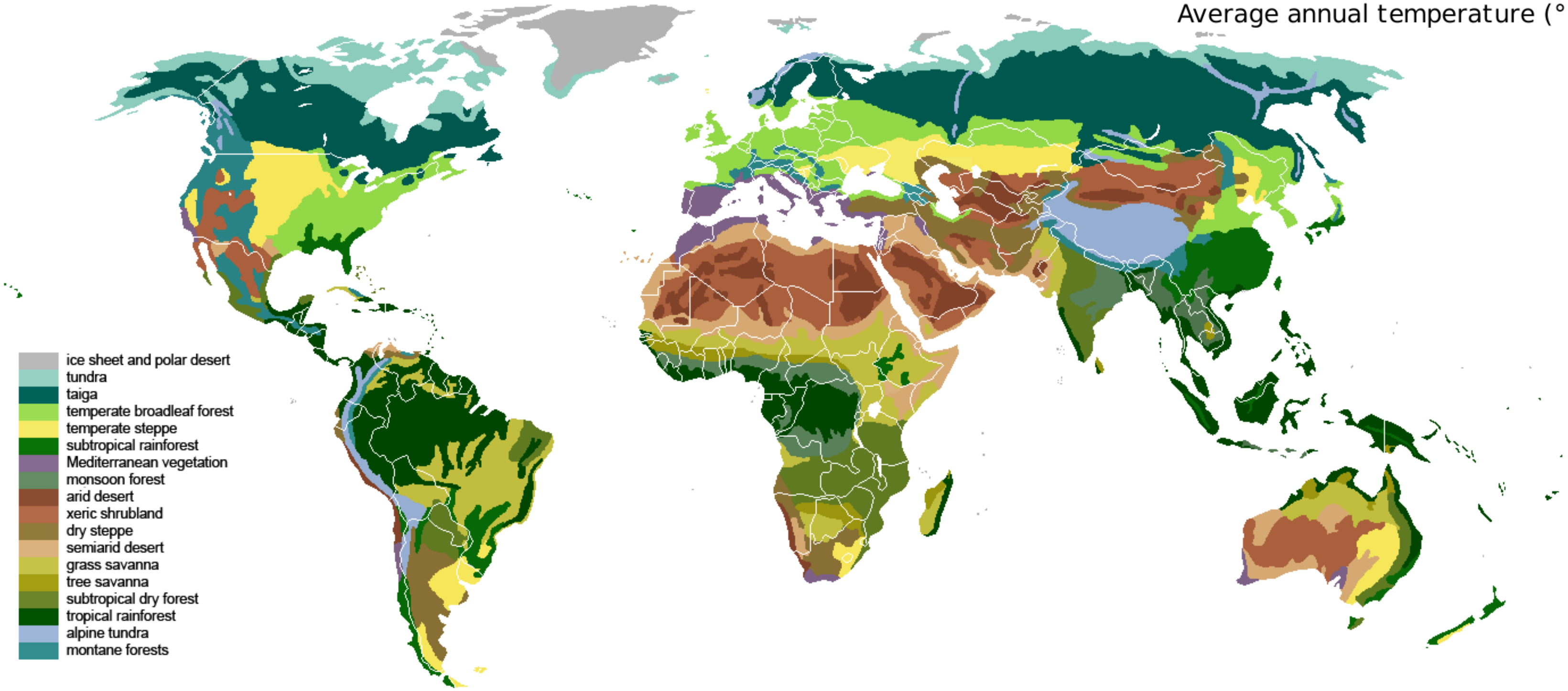


Biome associated to climate

- Climate are associated to typical biome : community of plant and animal adapted to some environment, in particular climate

- Human societies have been historically and are still directly determined by their local climate and biome. It affects living conditions and natural ressources.





Climate system

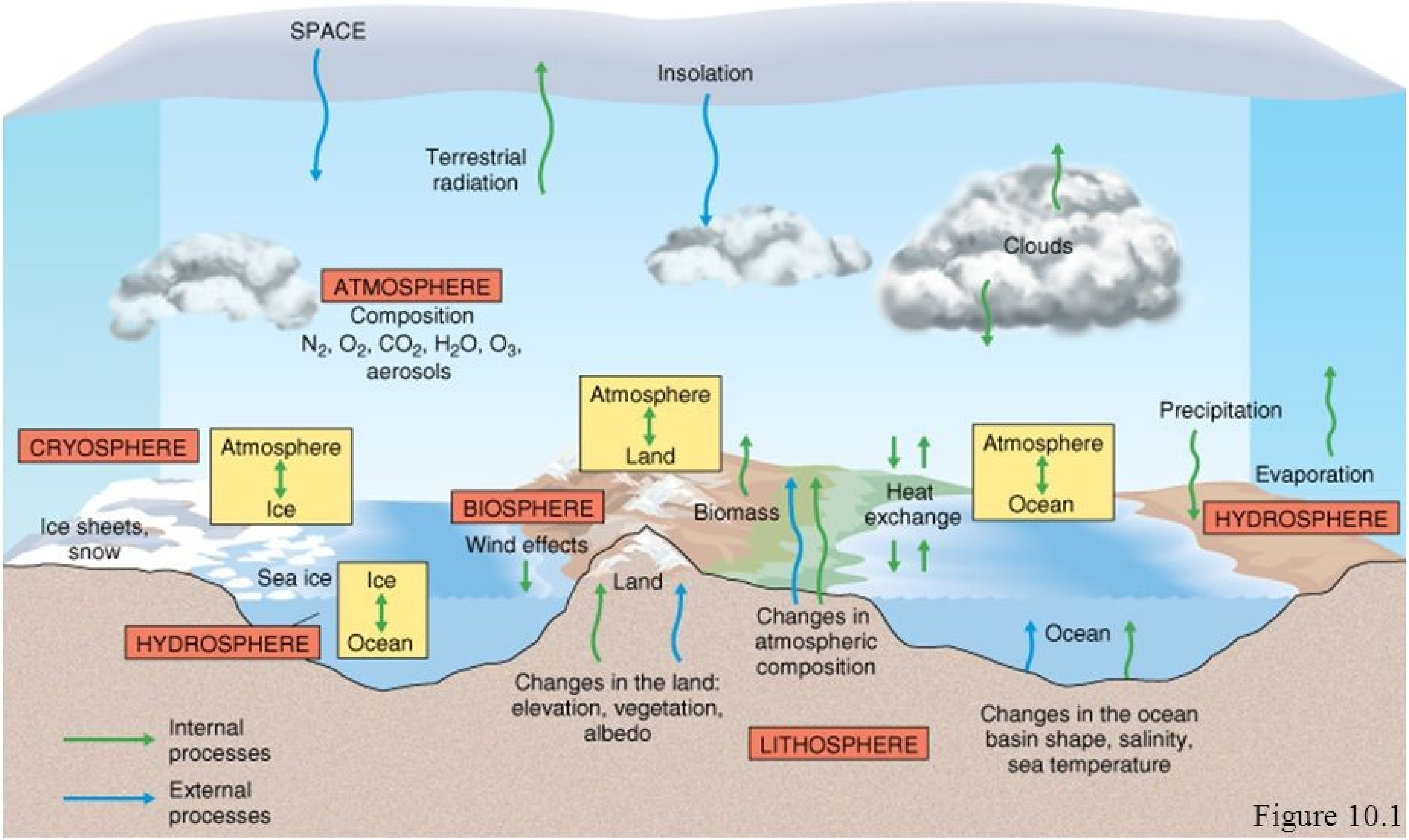
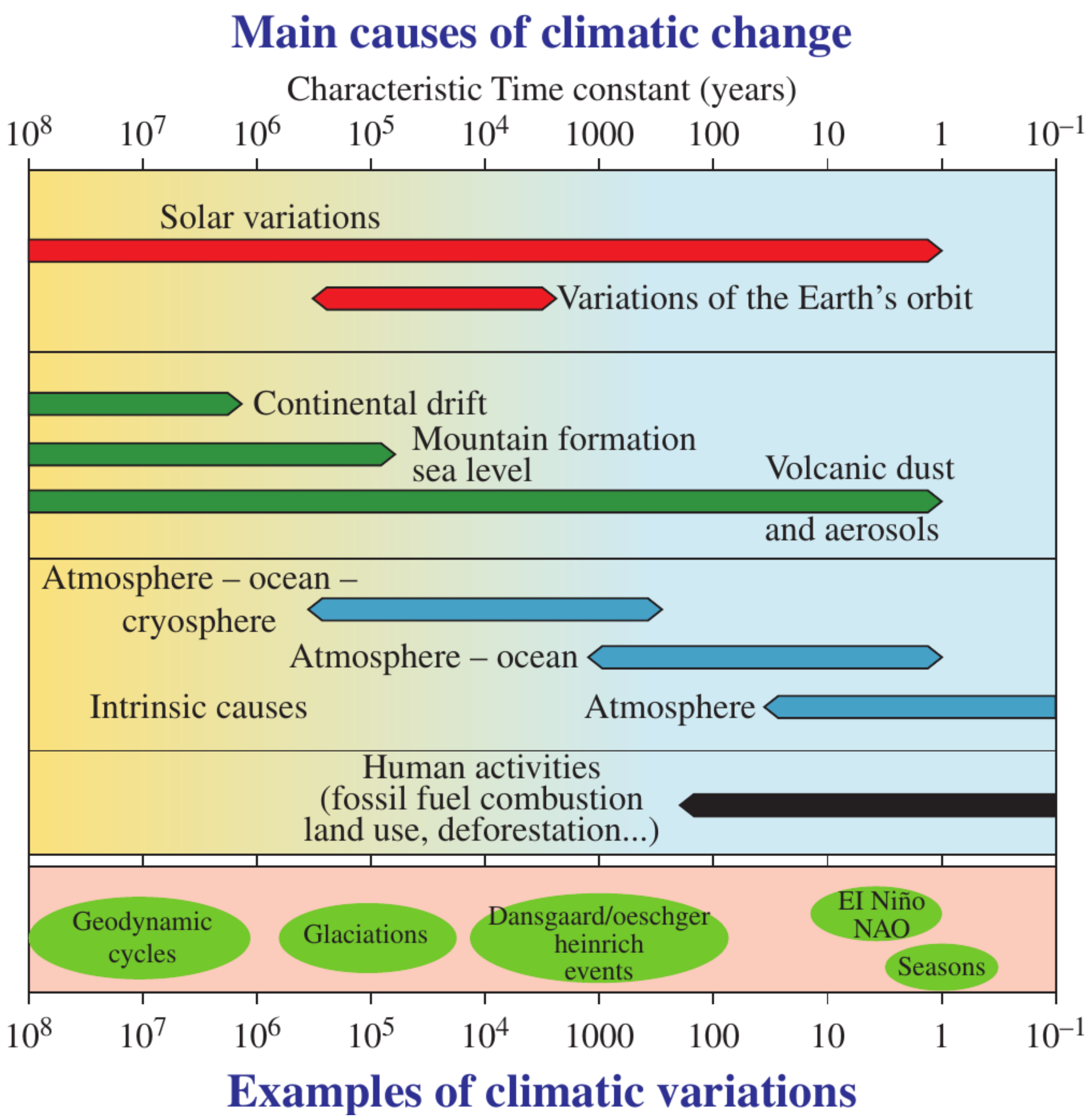


Figure 10.1

Climate change : causes and time scale



The climate machinery : an overview

- The energy essentially comes from the sun through radiative heating
- The radiative balance is essentially determined by albedo and the greenhouse effect that takes place in the atmosphere
- Over one year, the radiative input varies with seasons (astronomical effect) and inequality is inequally distributed over the surface of the earth
- The energy is redistributed by atmospheric and oceanic currents, partially stored in biosphere, hysphere and atmosphere.
- Human activities is significantly perturbing some natural chemical cycles (carbon, nitrogen, ozone) and modify the greenhouse effect, being at the origin of global warming and a new geological area : anthropocene
- => Today, modelling climate and its evolution in the near future requires to model human activities / societies (economy, demography,…). An interdisciplinary science (physics, chemistry, geology, biology,…) that is directly dependent on society science.

Radiative balance and greenhouse effect

Orders of magnitudes

- Solar energy is more than 1000 times larger than other sources
- This is globally, on space and time average : locally are during a short period of time, other sources can be relevant

Rayonnement électromagnétique reçu du Soleil (principalement visible et IR)	1,7 10^{17} W
Géothermie (radioactivités à période longue : ^{238}U, ^{235}U, ^{232}Th, ^{40}K)	~ 4,4 10^{13} W
Civilisation en 2010 (~10^9 humains consommant 10 t de pétrole/an)	1,6 10^{13} W
Énergie rotative dissipée par les marées	2,8 10^{12} W
Vent solaire (pour « cible magnétosphérique » de 25 R_{Terre} ~ 10^{14} W)	~ 2 10^{11} W
Rayonnement du fond cosmologique (corps noir* à 2,7 K)	1,6 10^9 W
Rayonnement électromagnétique reçu des étoiles (visible, IR)	~ 1,3 10^9 W
Rayonnement cosmique (protons, alphas…)	9 10^8 W
Météorites (~ 30 000 tonnes par an, supposant v_{impact} ≈ 20 km/s)	~ 2 10^8 W

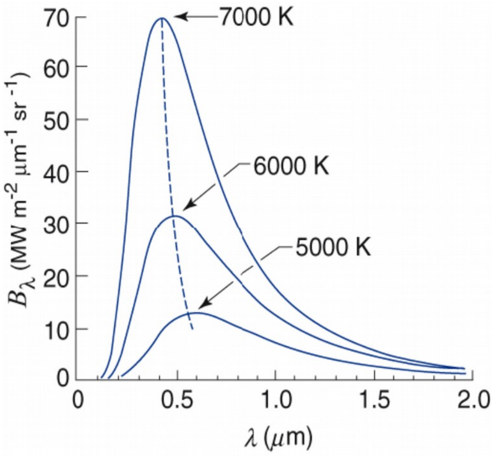
Black body radiation summary

- Stefan-Boltzmann law for black body emission at temperature T

$$M_{\text{corps noir}} = \sigma T^4 \qquad \sigma = 5.67 \times 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}$$

- Planck's law for wave-length distribution of emission

$$B_\lambda(T) = \frac{C_1\, \lambda^{-5}}{\pi\, \left(e^{C_2/\lambda T} - 1\right)}$$



- Emissivity and grey body

$$M_{\text{corps gris}} = \epsilon\, \sigma\, T^4$$

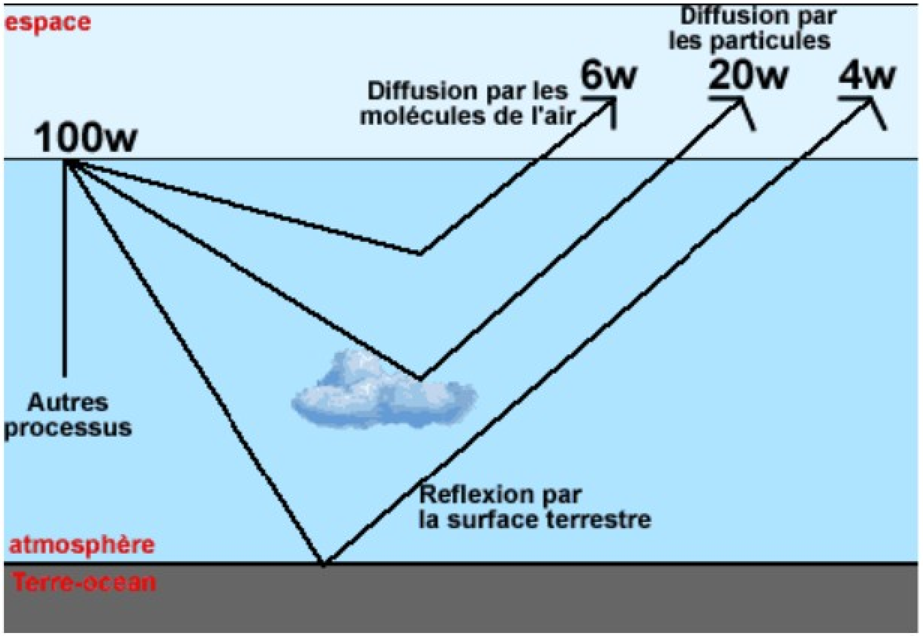
- Second Kirchoffs law :
absorption coef=emissivity coef

$$\epsilon_\lambda = \alpha_\lambda$$

Matériau	Emissivité ϵ
Aluminium	0.02
Cuivre poli	0.03
Nuages type cirrus	0.10 à 0.90
Nuages type cumulus	0.25 à 0.99
Cuivre oxydé	0.5
Béton	0.7 à 0.9
Carbone	0.8
Lave (volcan actif)	0.8
Neige âgée	0.8
Ville	0.85
Désert	0.85 à 0.9
Peinture blanche	0.87
Brique rouge	0.9
Herbe	0.9 à 0.95
Eau	0.92 à 0.97
Peinture noire	0.94
Forêt	0.95
Suie	0.95
Neige fraîche	0.99

Albedo

- Part of incident radiation that is reflected back to space
- Mean albedo for Earth $A_b \simeq 0.30$



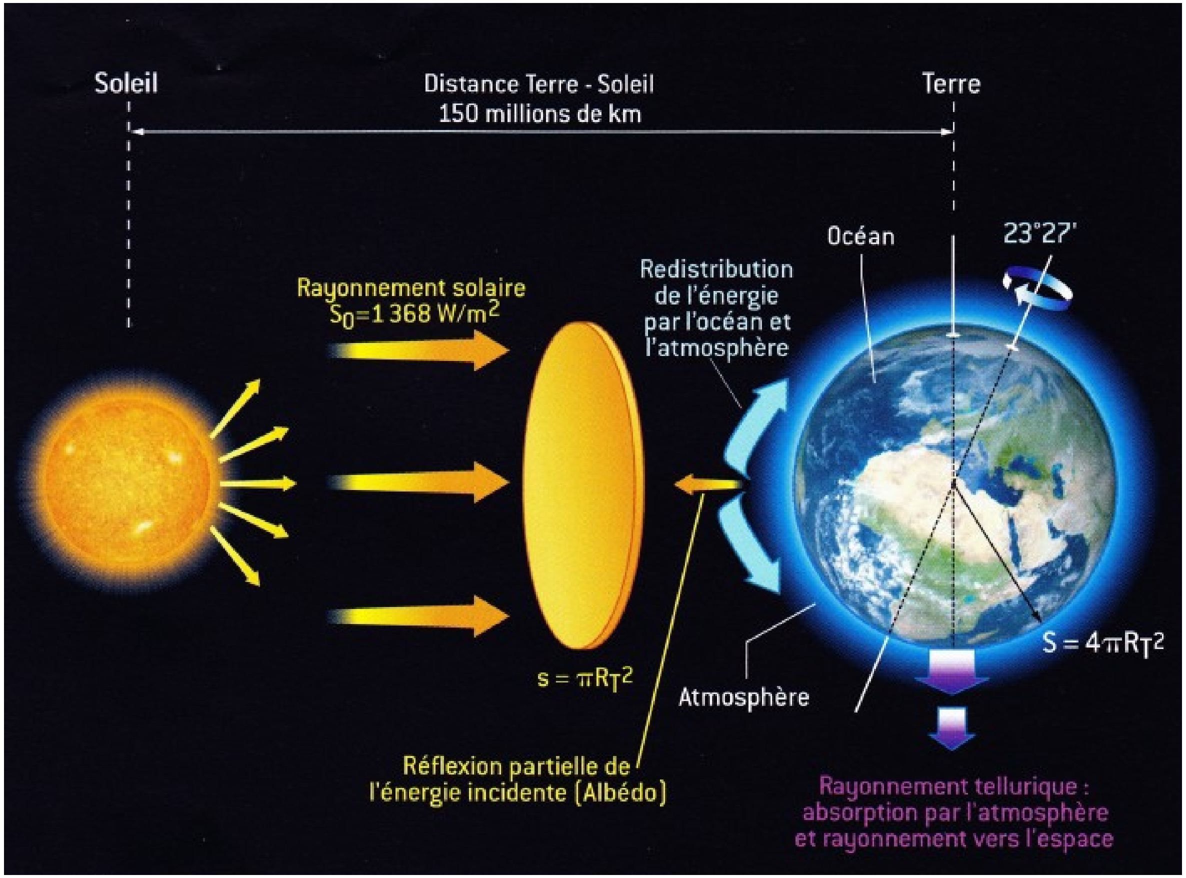
Type	albédo A
Surface de lac	0.02 à 0.04
Surface de la mer	0.05 à 0.15
Asphalte	0.07
Mer calme (soleil au zenith)	0.10
Forêt équatoriale	0.10
Roches sombres, humus	0.10 à 0.15
Ville	0.10 à 0.30
Forêt de conifères	0.12
Cultures	0.15 à 0.25
Végétation basse, verte	0.17
Béton	0.20
Sable mouillé	0.25
Végétation sèche	0.25
Sable léger et sec	0.25 à 0.45
Forêt avec neige au sol	0.25
Glace	0.30 à 0.40
Neige tassée	0.40 à 0.70
Sommet de certains nuages	0.70
Neige fraîche	0.75 à 0.95

“here comes the sun”

Solar constant : $\mathcal{F}_s = 1368 \text{ W m}^{-2}$

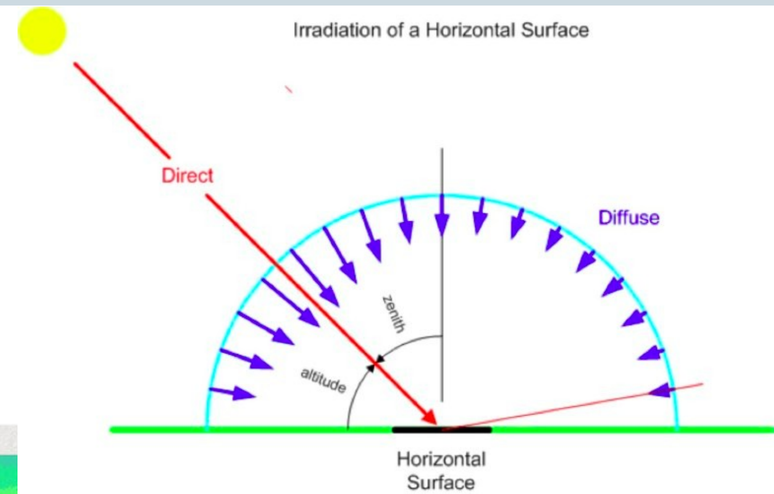
Mean albédo : $A_b \simeq 0.30$

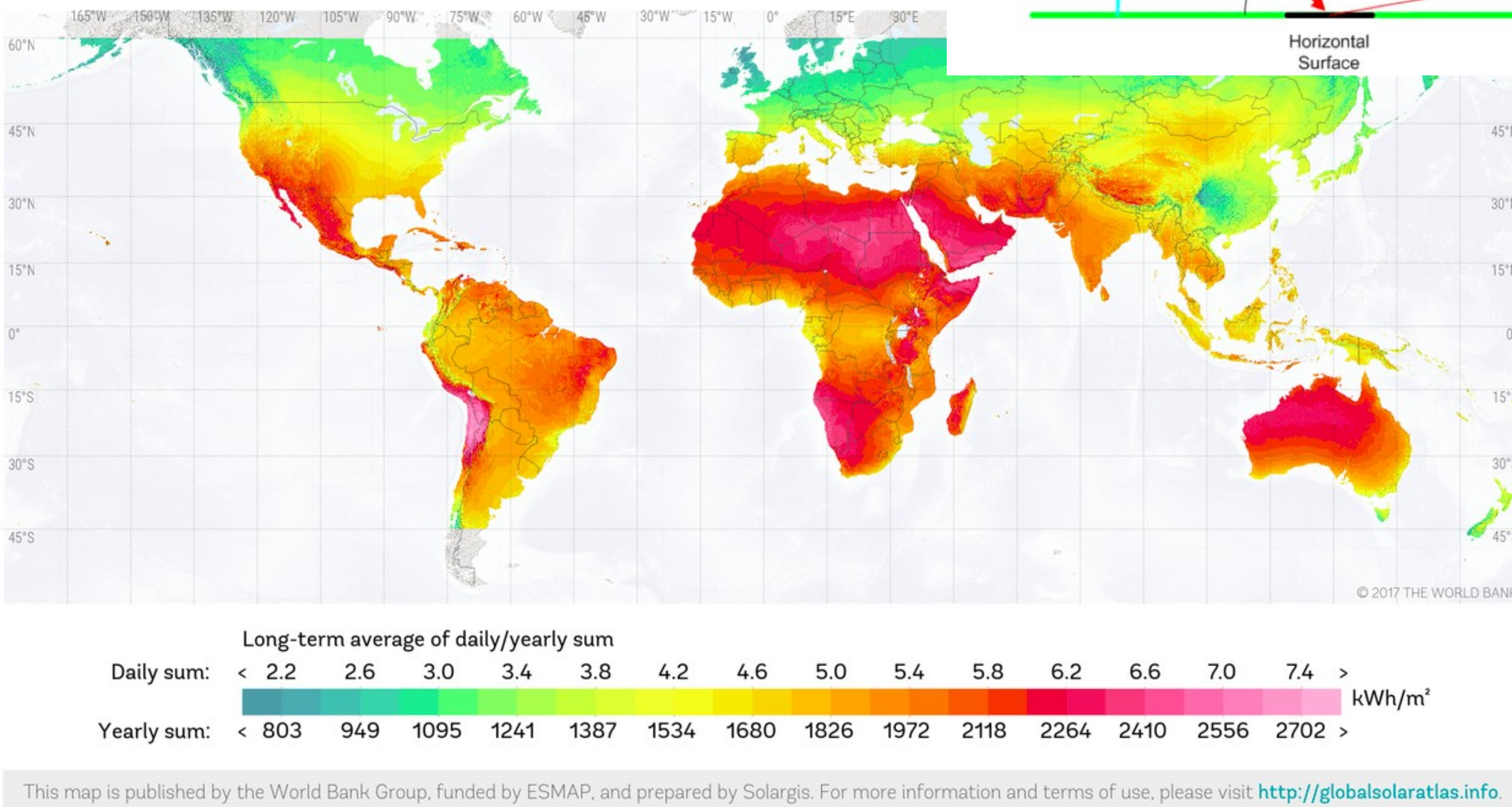
Average flux on Earth surface : $\mathcal{F}'_s = \frac{\mathcal{F}_s}{4}$ $\qquad \mathcal{F}'_s(1 - A_b) \simeq 239 \; W/m^2$



Global horizontal irradiation

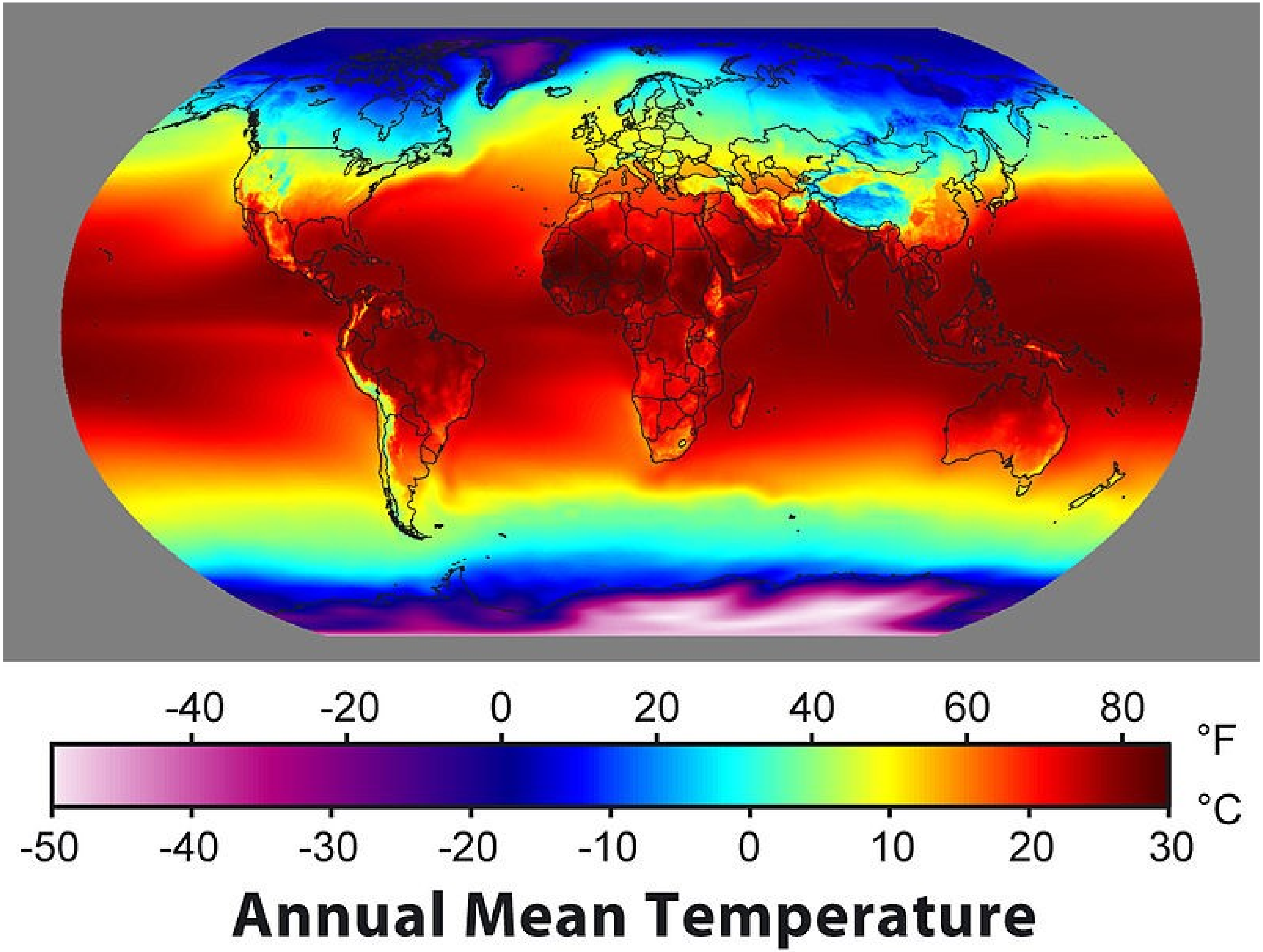
- Depend on lattitude and local albedo
  7.4 $kWh.m^{-2}/day = 308\ Wm^{-2}$





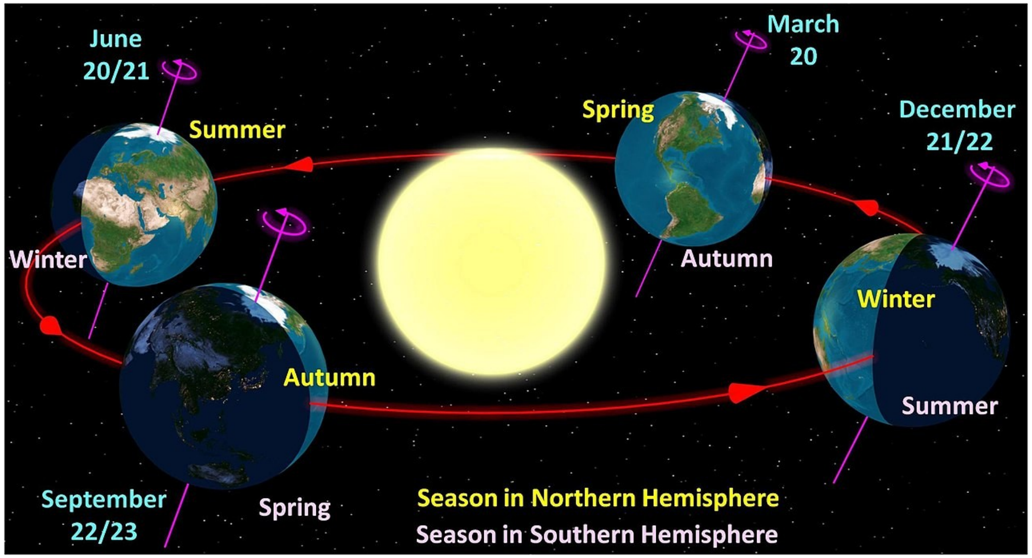
Lattitude distribution of temperature

- Crude effect of inclinasion

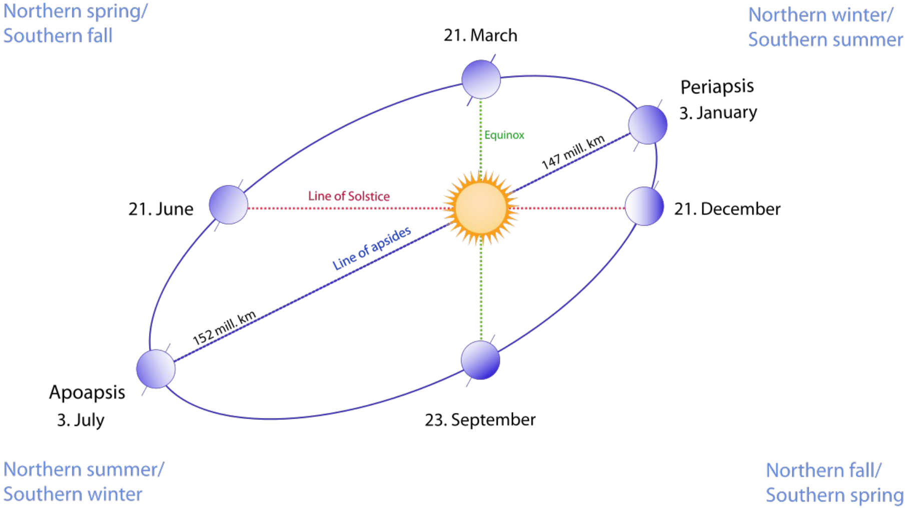


Seasons I (time scale = year)

- First : daily variation of sunlight !
- One year => basic unit of time for averaging in climatology !
- Due to orbit cycle and axial inclination => variation of incident sunlight



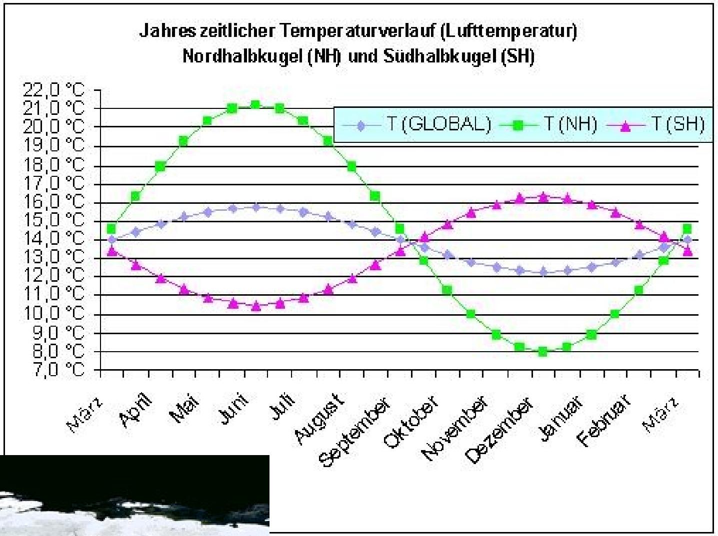
- Ellipticity has a small effect : earth is at its highest distance in summer for North hemisphere

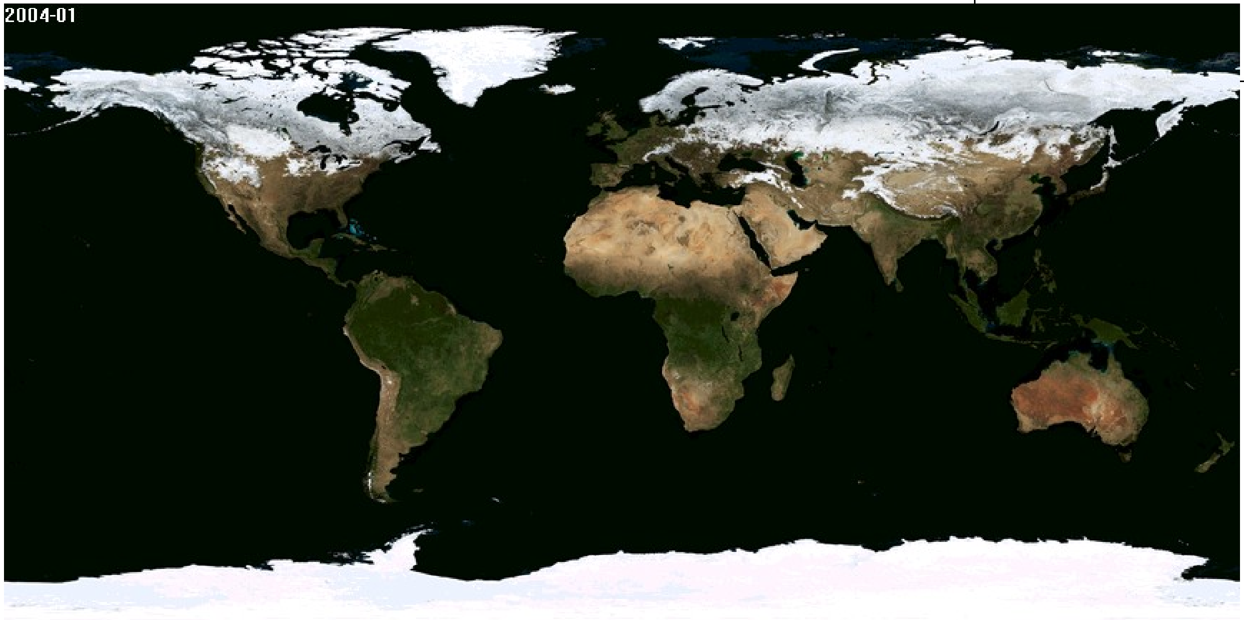


Seasons II

- Seasonal lag : warming oceans and land takes time (thermic inertia) => maximum temperature occurs after maximum of insolation

- Difference between north and south hemispheres mostly due to inequal repartition of land and oceans => rôle of continent distribution

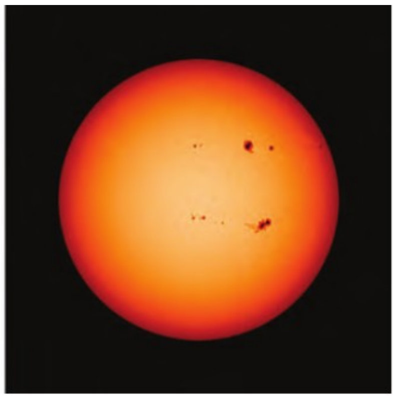


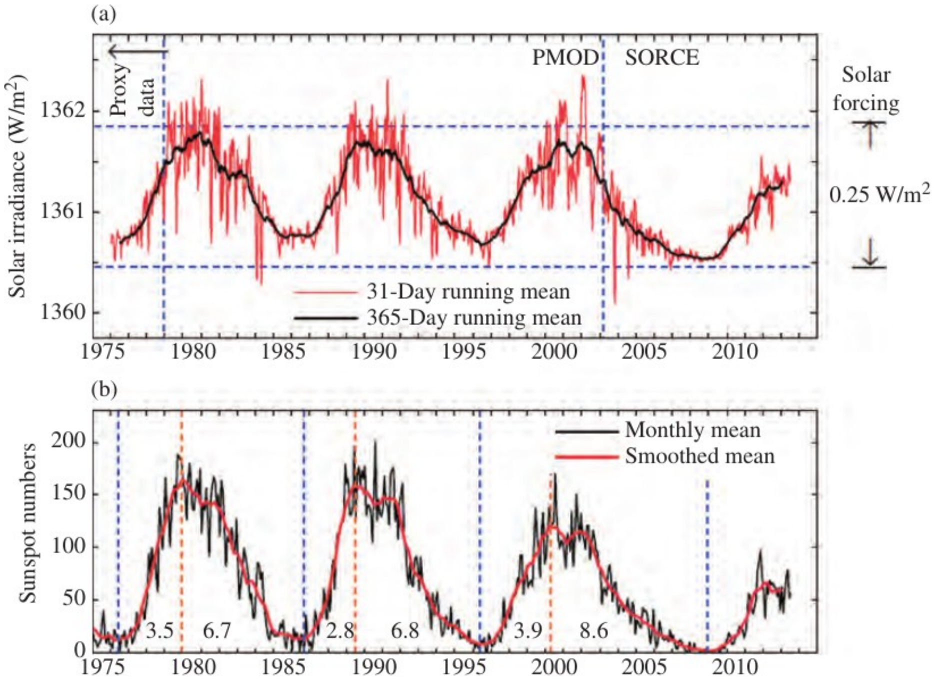


Solar activity (time-scale ~ 10 years)

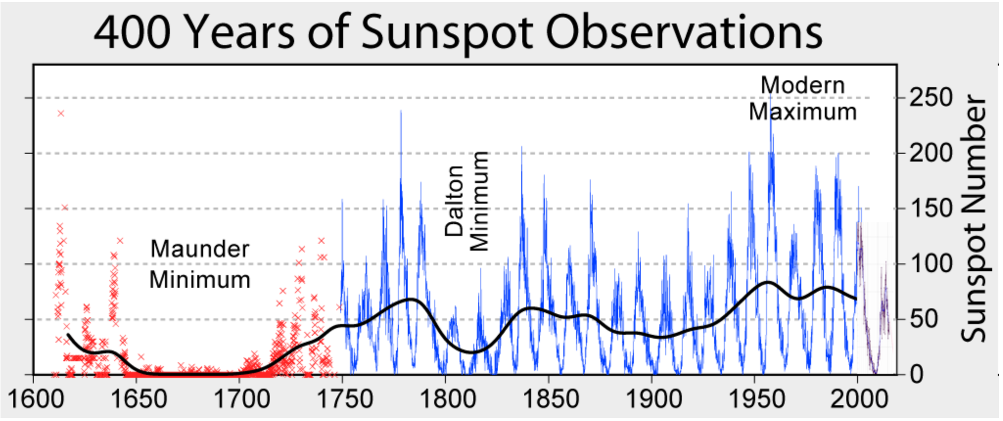
- The sun radiation power varies slightly with time

- Strongly correlated with sun spots





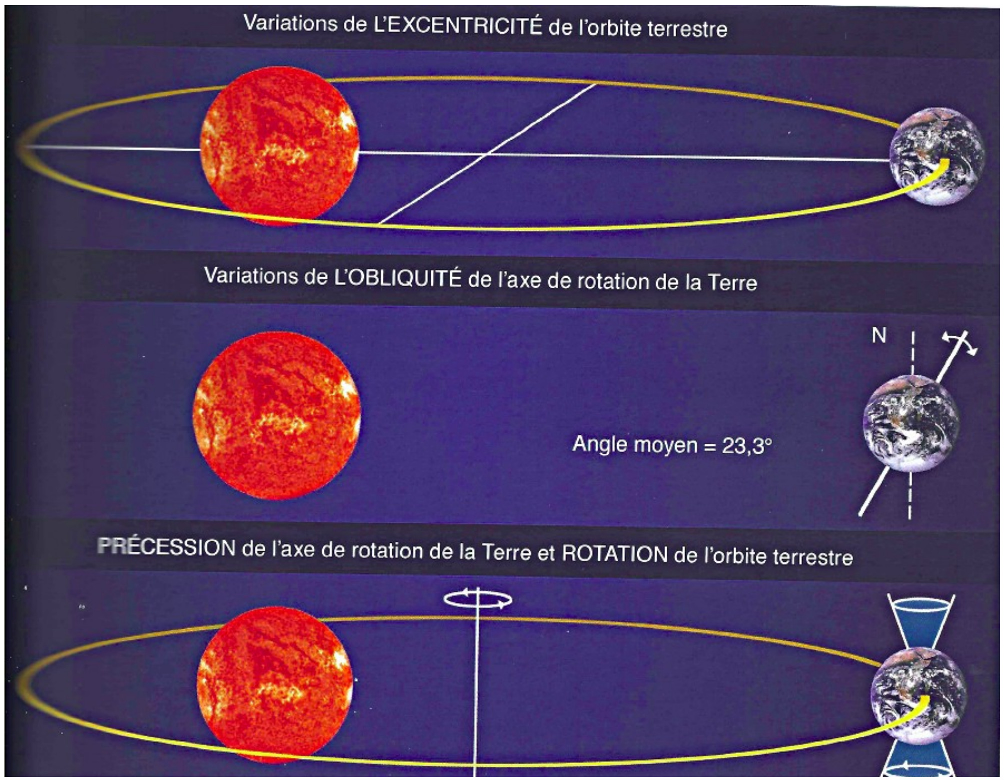
- Helps reconstruct the past
  => contribution to « little ice-age »

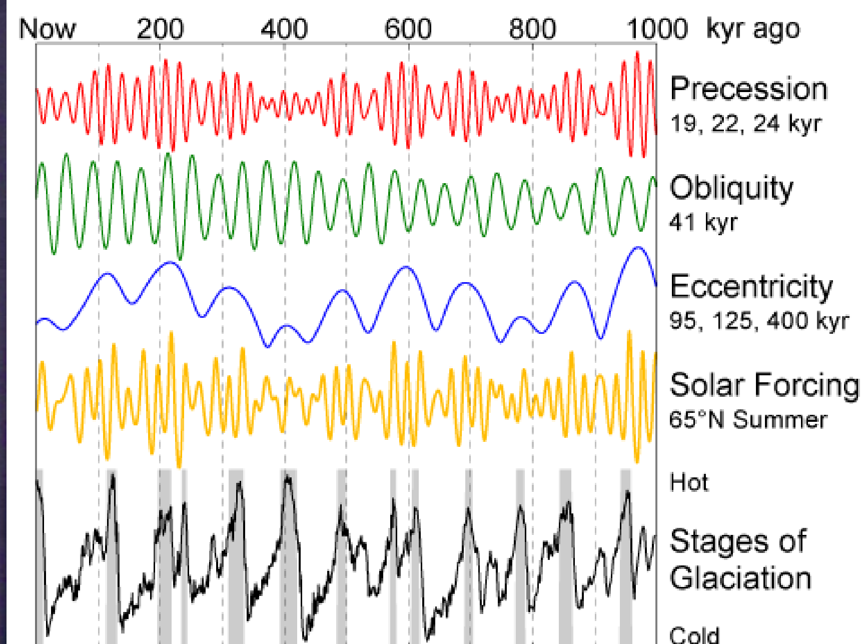


Astronomical variability (time scale > 20.000y)

Milankovic cycles

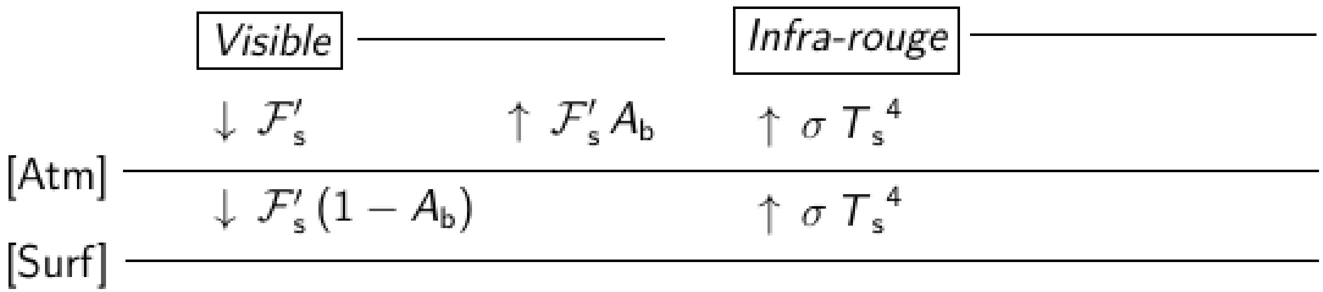
Good correlation with glaciation periods





Greenhouse effect - equivalent temperature

Only albedo is taken into account



Radiative equilibrium gives :

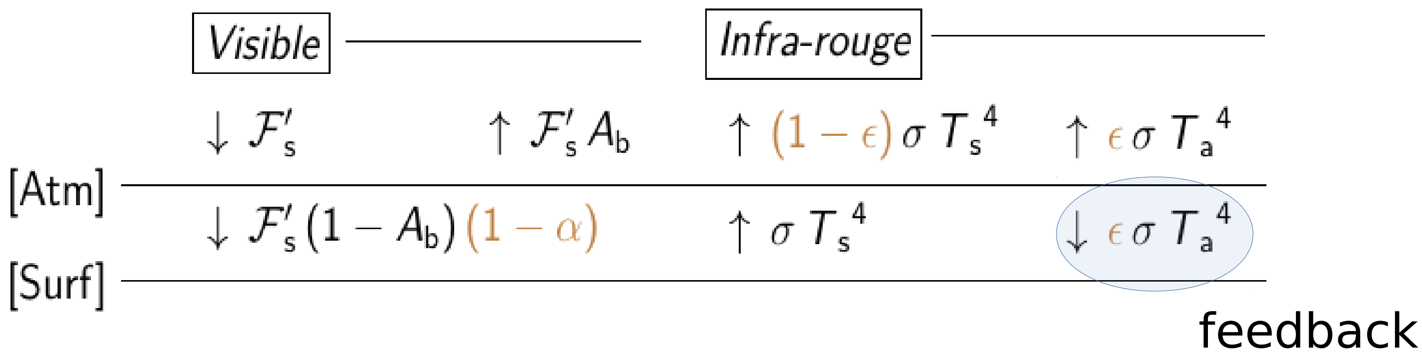
$$T_{\mathrm{eq}} = \left[\frac{\mathcal{F}'_{\mathrm{s}} \, (1 - A_{\mathrm{b}})}{\sigma} \right]^{\frac{1}{4}}$$

Significant feedback from the atmosphere

	Mercure	**Vénus**	**Terre**	**Mars**	**Titan**
d_{soleil} (UA)	0.39	0.72	1	1.5	9.5
$\mathcal{F}_{\mathrm{s}}$ (W m^{-2})	8994	2614	1367	589	15
A_{b}	0.06	0.75	0.31	0.25	0.2
T_{surface} (K)	100/700 K	730	288	220	95
T_{eq} (K)	439	232	254	210	86

Greenhouse effect - single shell model

Atmosphere absorbs visible light (ozone, aerosols)
Atmosphere absorbs IR and reemits it in all directions



Surface temperature

$$T_s = \sqrt[4]{\frac{1-\frac{\alpha}{2}}{1-\frac{\epsilon}{2}}}\,T_{eq} \qquad T_{eq} = \left[\frac{\mathcal{F}'_s\,(1-A_b)}{\sigma}\right]^{\frac{1}{4}}$$

Conclusion, we have the key ingredients of *direct* effects :
* incoming solar flux
* albedo (visible light)
* absorption (visible light)
* absorption and reemission (infrared)

Greenhouse effect - reality

Mutlishell models

atmosphere stratification and temperature profile

Emissivity and surface albedo in visible depends on the nature of the surface

detailed description of absorption/emission and reflexion/diffusion by molecule/particules

=> use softwares (MODTRAN,...)

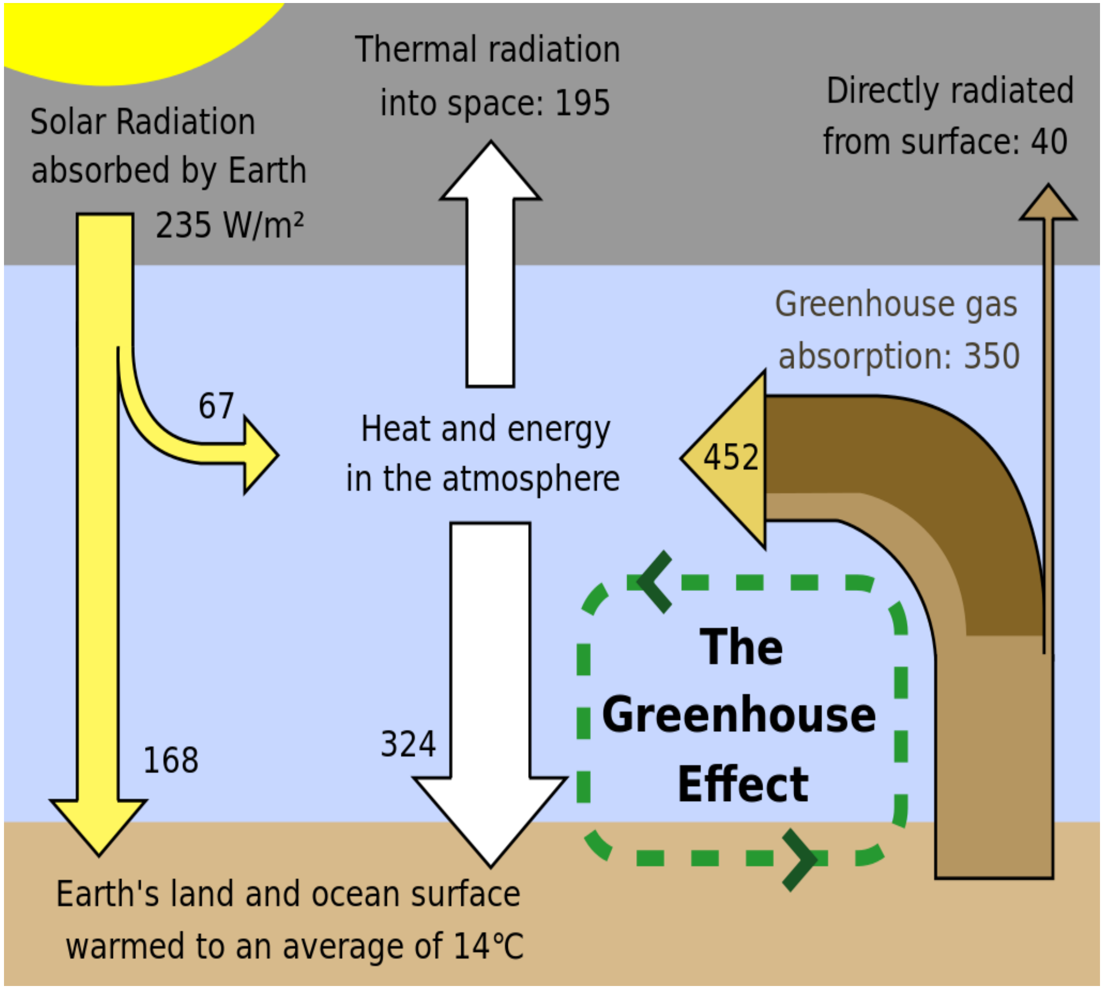
Convection, conduction, latent heat participate to the energy tranfer from the surface to the atmosphere.

Chemistry reactions occur in the atmosphere

=> requires dynamical description of the atmosphere

« Sky is the limit »

Radiative balance in **W/m²**



Detailed balance

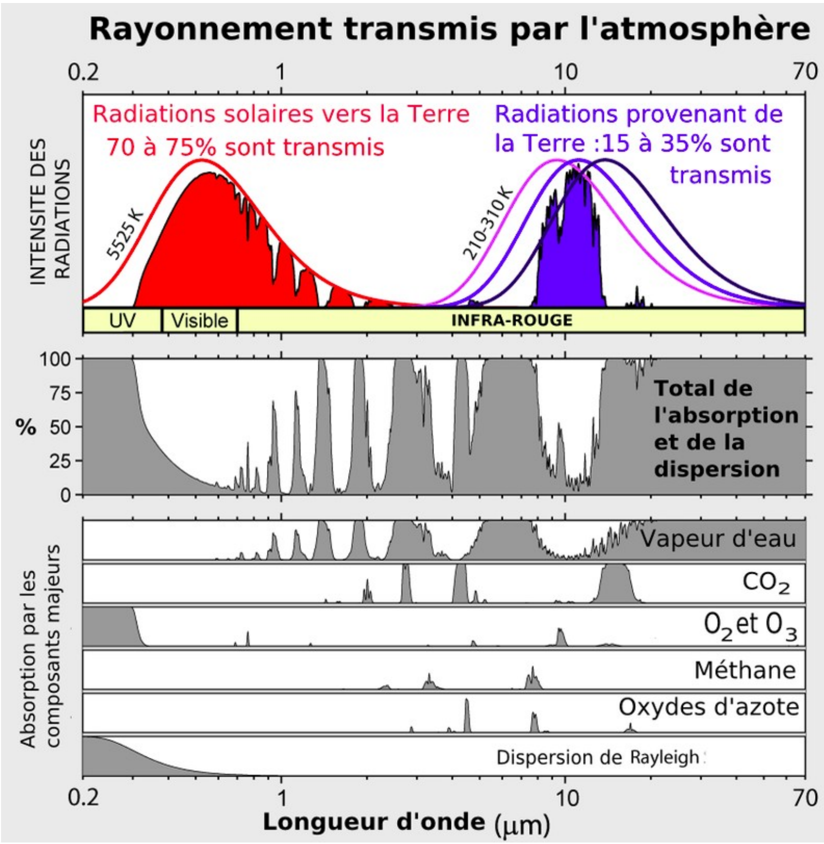
235 = 195 + 40

67 + 452 = 324 + 195

168 + 324 = 452 + 40

Greenhouse gases

- Principaly H_20 and CO_2 but also CH_4, N_2O, CF_4, SF6…



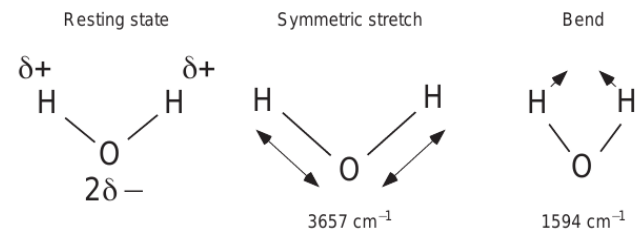


Figure 4-2 Vibrational modes of a water molecule that interact with infrared light in the atmosphere.

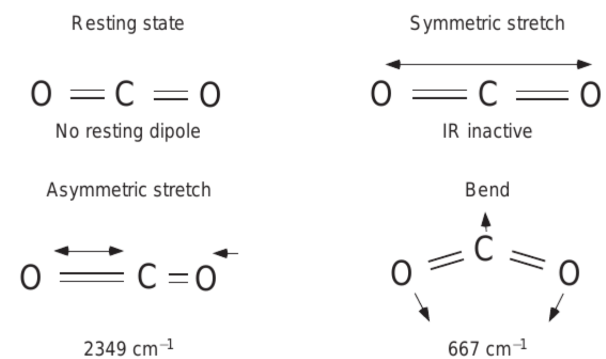


Figure 4-1 Vibrational modes of a CO_2 molecule that interact with infrared light in the atmosphere.

- Relative natural contributions :

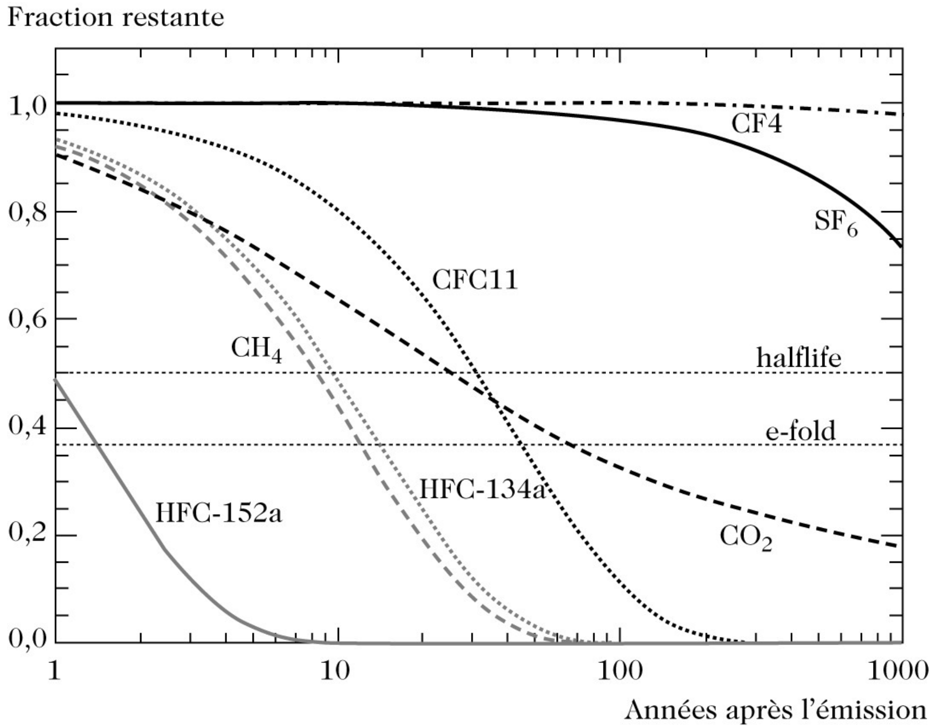
H_2O	CO_2	O_3	$CH_4 + N_2O$
60 %	26 %	8 %	6 %

- Relative anthropic contributions :

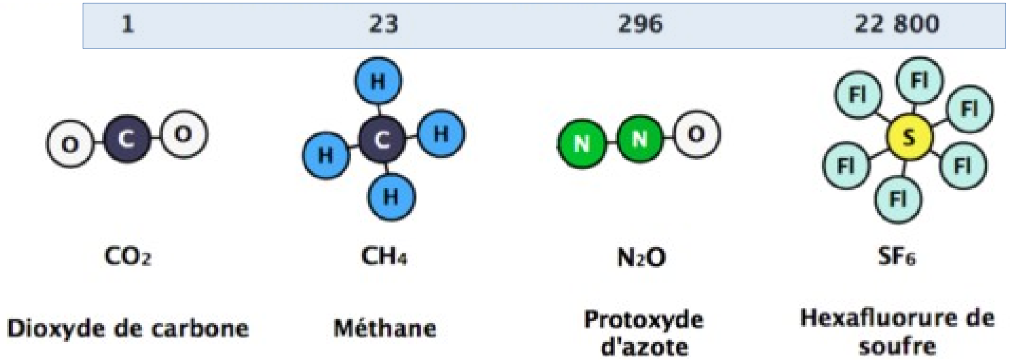
CO_2	CH_4	CFCs	O_3	N_2O
56 %	16 %	12 %	11 %	5 %

Global warming potential

- Residence time of excess emission

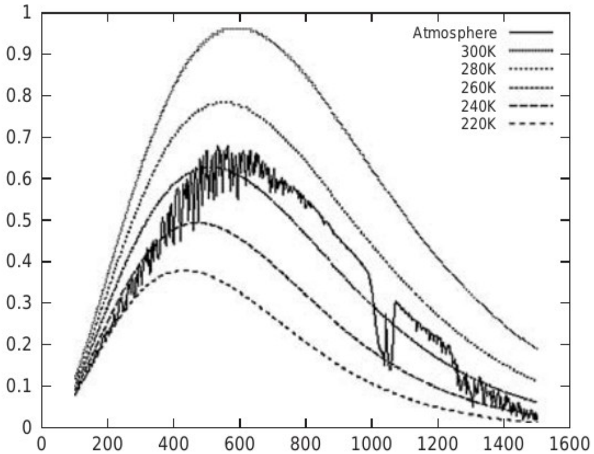


- Effect relative to carbon dioxide (explained latter)



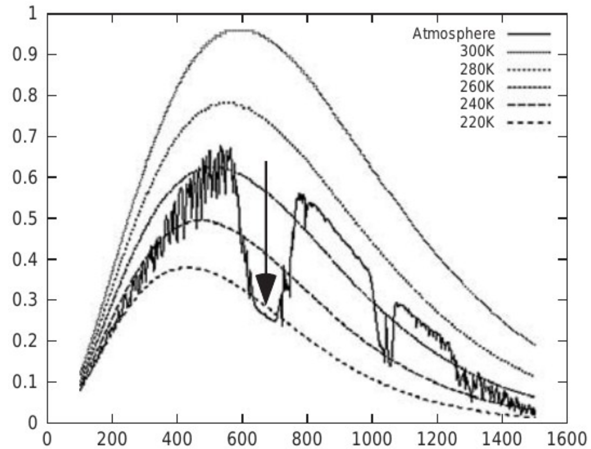
Graphical view on the greenhouse effect

- One adds CO2 and requires the radiative power emitted through the atmosphere to be kept constant
- Plots of Black body radiation emitted at the top of the atmosphere



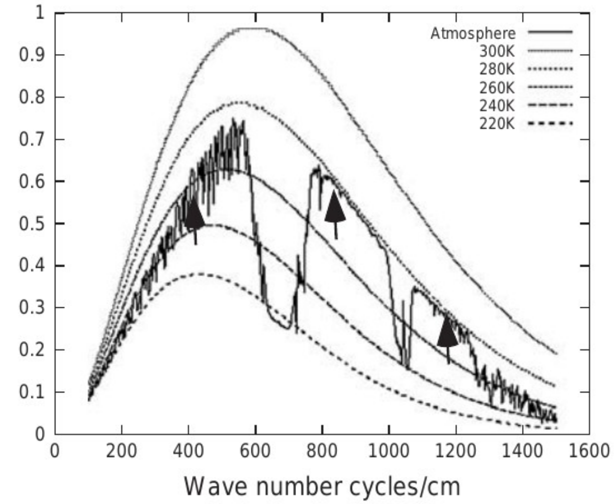
No CO_2

$I_{out} = 249\ W/m^2$



1000 ppm CO_2

$I_{out} = 223\ W/m^2$



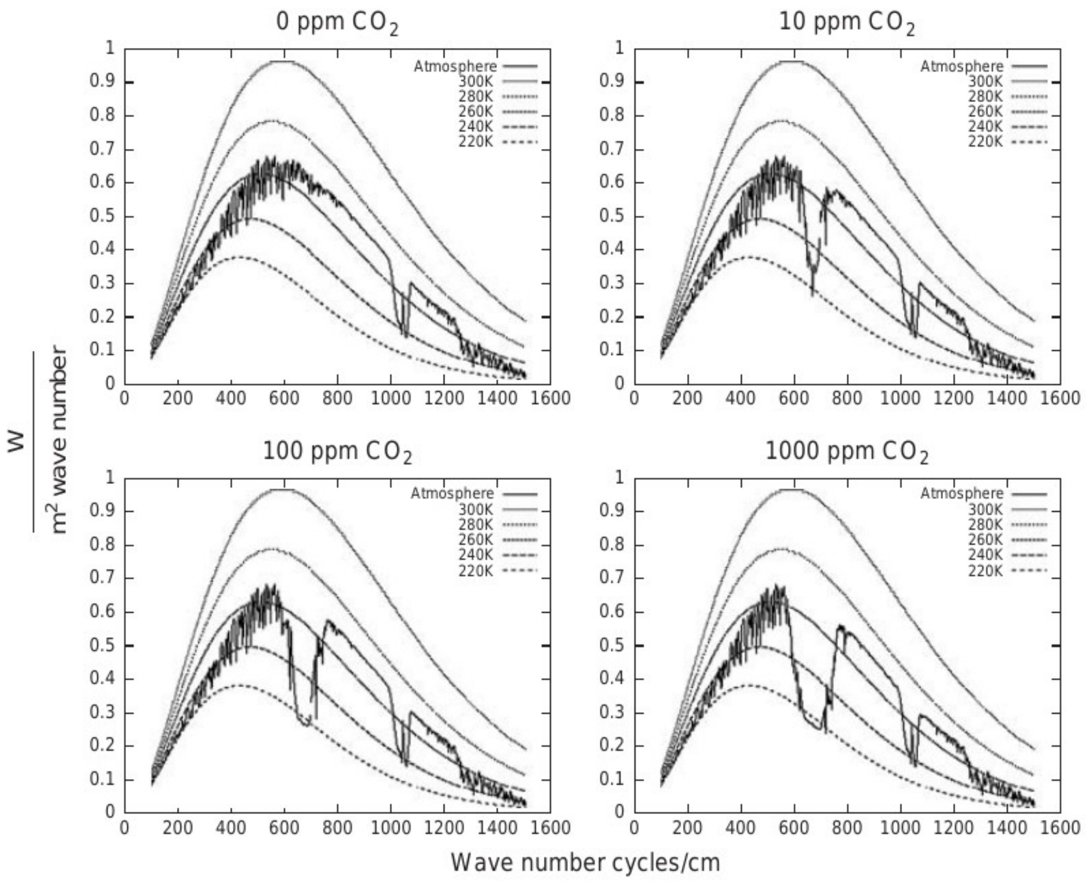
1000 ppm CO_2

8.5 K warmer

$I_{out} = 249\ W/m^2$

Band saturation effect for CO2

- For a fixed temperature, adding more CO2 has less and less effect because of band saturation effect.
- ...but the climate system reacts non-linearly (see climate sensitivity hereafter)
- Plots of Black body radiation emitted at the top of the atmosphere



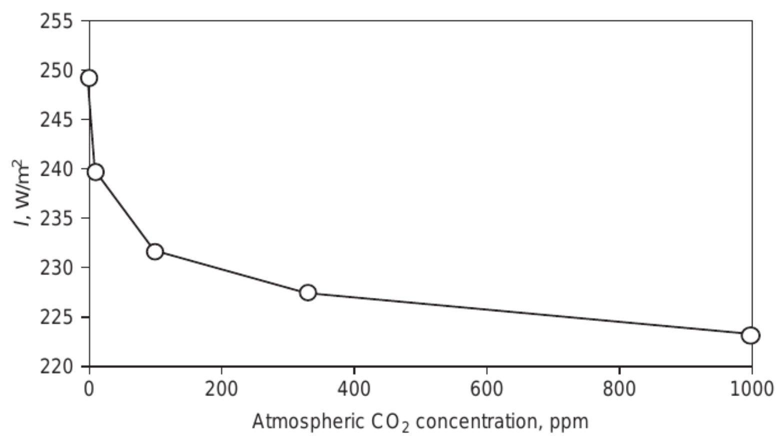


Figure 4-6 Band saturation viewed in a different way from Figure 4-5. This is a plot of the total energy flux carried by all infrared light, which is proportional to the area under the spectrum curves in Figure 4-5. The outgoing energy flux is less sensitive to CO_2 when the CO_2 concentration is high.

Aerosols

- Definition : small particles either solid or liquid in suspension in the atmosphere coming from natural (volcanism, forest fire,...) or human activities (combustion,...)

- Examples : dust, sand from desert, organic or salt compounds disolved in water (fog), sulfite particles (volcanoes)

- They help to nucleate water drops/ice in clouds

- They have a relatively short resident time in the troposphere but long resident time in the stratosphere (over a few years).

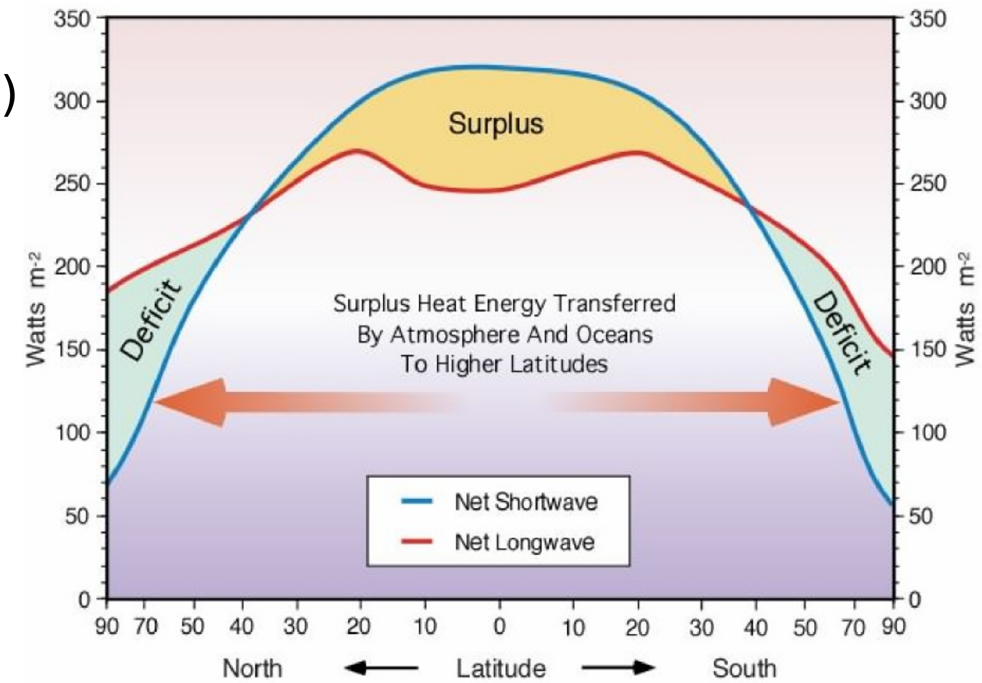
- They diffuse and reflect radiation through diffusion processes and then usually contribute to increase the albedo.

Energy redistribution and global circulations

From equator to the poles

- Partial redistribution of heat with latitude due do atmosphere (~50%) and oceans (~50%) circulations

  => moderates the difference of temperature between the poles and the equator



- Orders of magnitude

  For kinetic energy density : $\rho v^2/2$

  $v_{atm} = 10\ m.s^{-1}$; $\rho_{atm} = 1\ kg.m^{-3}$

  $v_{oc} = 0.1\ m.s^{-1}$; $\rho_{oc} = 1000\ kg.m^{-3}$

  For heat capacity

  $m_{atm} = 3\ 10^{18}\ kg$

  $c_{atm} = 1000\ J.kg^{-1}K^{-1}$

  $m_{oc} = 300\ m_{atm}$

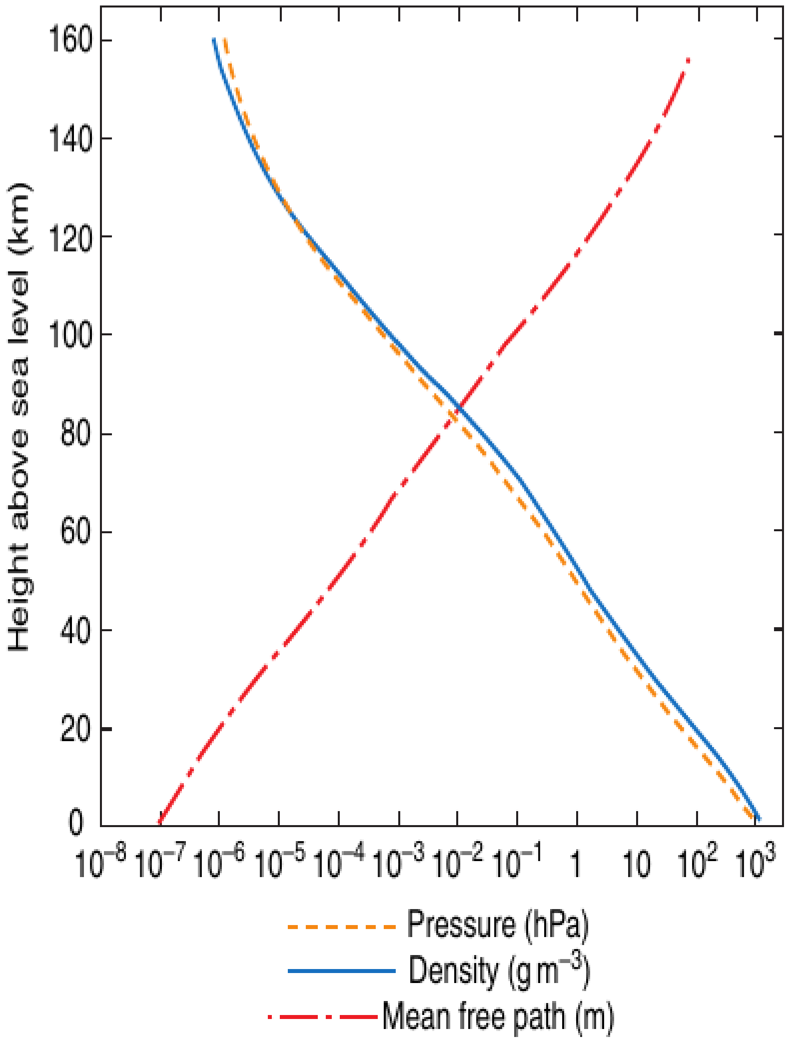
  $c_{oc} = 4000\ J.kg^{-1}K^{-1}$

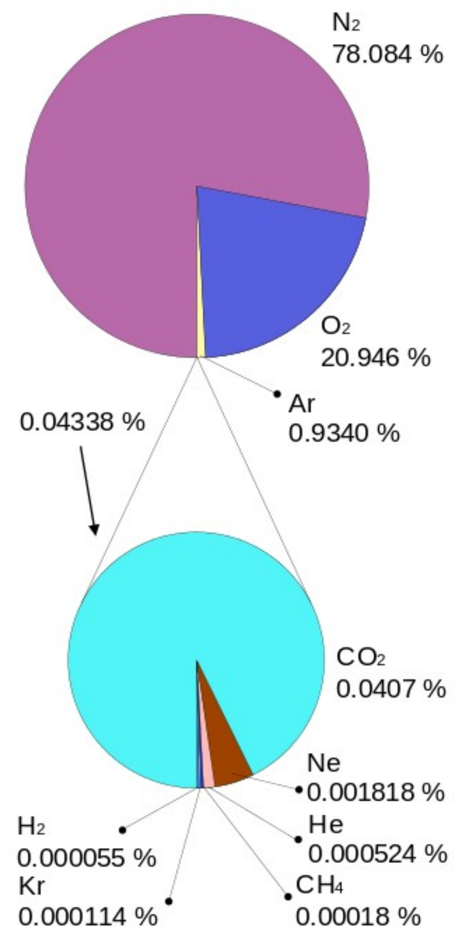
	atmosphere	ocean
Kinetic energy density	$50\ J.m^{-3}$	$5\ J.m^{-3}$
Heat capacity	$10^{21}\ J.K^{-1}$	$4\ 10^{24}\ J.K^{-1}$

Atmospheric pressure profile and composition

- A relatively good mixture of perfect gases with an exponential profile of density and pressure. Its mass is about 5 10^{18}kg

$$P \sim P_0\, e^{-z/H}$$



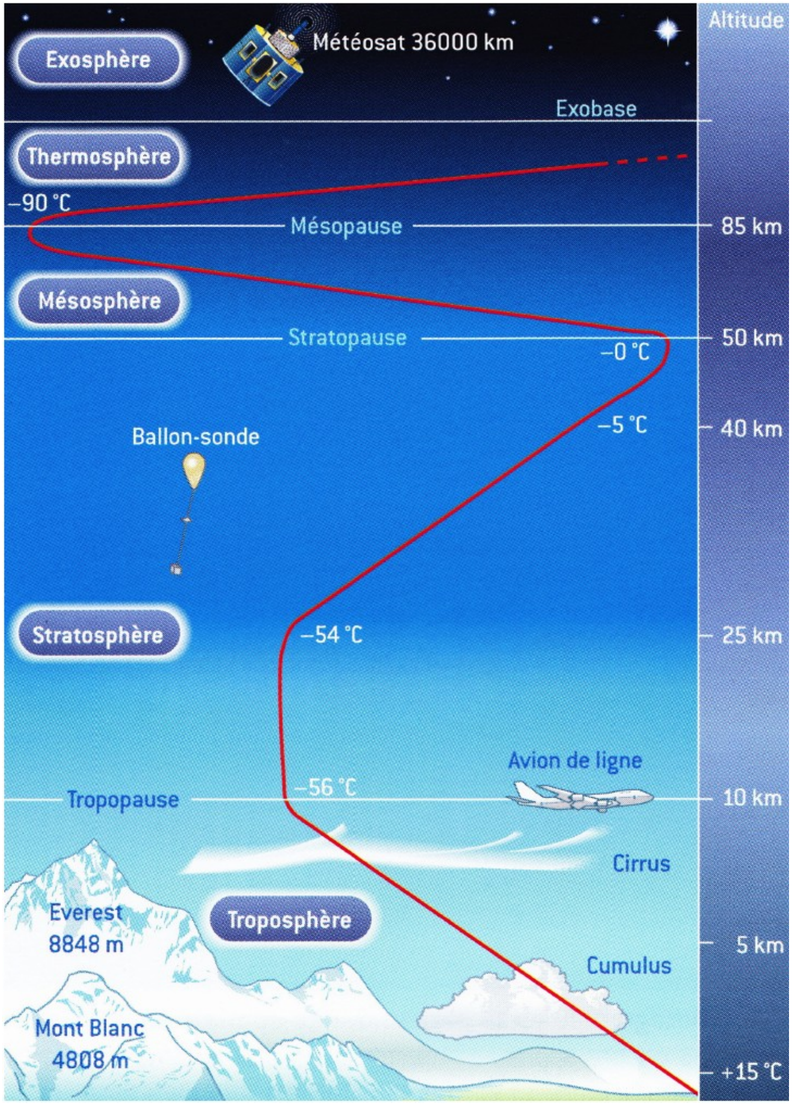


Atmosphere temperature profile and stability

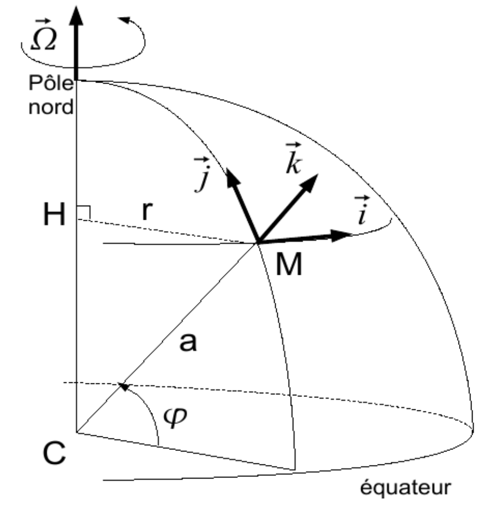
- **Troposphere** is unstable towards convection : when a parcel of air is heated at the ground, it goes up and cool down with altitude. It is replaced by cooler air at the bottom inducing vertical circulation that mixes the gas.

- **Stratosphere** is stable: the reason why the temperature increases with altitude in the stratosphere is because of the presence of ozone O_3 that absorbs UV light from the sun and this heats up the gas

  there is no clouds, no water and resident time of molecules are very long in the stratosphere



Coriolis force dominates on large scales



For the horizontal motion velocity : $\mathbf{V}_h = u\mathbf{i} + v\mathbf{j}$

Coriolis force: $\mathbf{F}_C = -f\,\mathbf{k} \wedge \mathbf{V}_h$ with $f = 2\,\Omega\,\sin\phi$

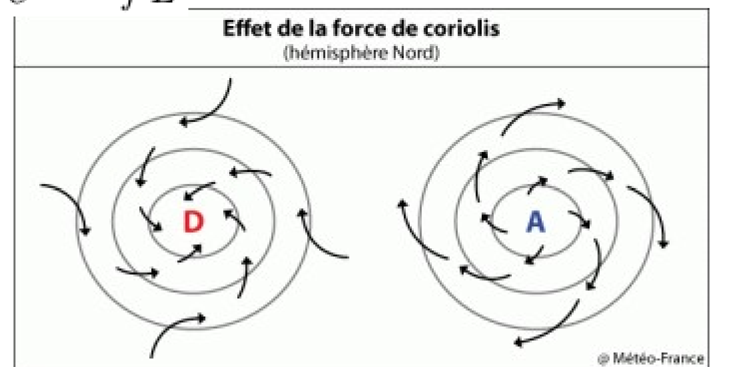
Pressure force $\mathbf{F}_P^H = -\frac{1}{\rho}\begin{pmatrix}\frac{\partial P}{\partial x}\\ \frac{\partial P}{\partial y}\end{pmatrix}$

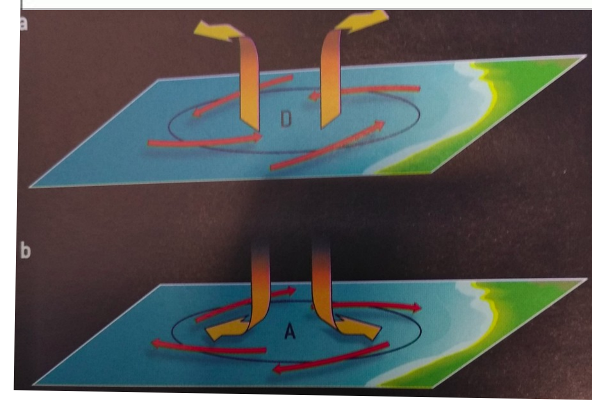
Equation of motion : $\frac{d\mathbf{V}_h}{dt} + f\mathbf{k} \wedge \mathbf{V}_h = \mathbf{F}_P$

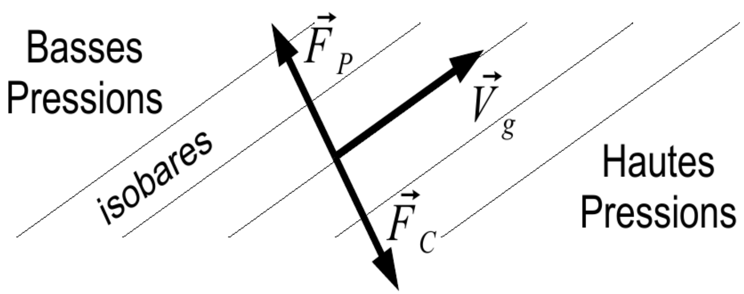
Rossby number <<1 at large scales L: $\mathcal{R} = \frac{U^2/L}{f\,U} = \frac{U}{f\,L}$

Geostrophic wind, from $f\mathbf{k} \wedge \mathbf{V}_g = \mathbf{F}_P$ one gets

$$\mathbf{V}_g = \begin{pmatrix}u\\ v\end{pmatrix} = \begin{pmatrix}-\frac{1}{\rho\,f}\,\frac{\partial P}{\partial y}\\ \frac{1}{\rho\,f}\,\frac{\partial P}{\partial x}\end{pmatrix}$$

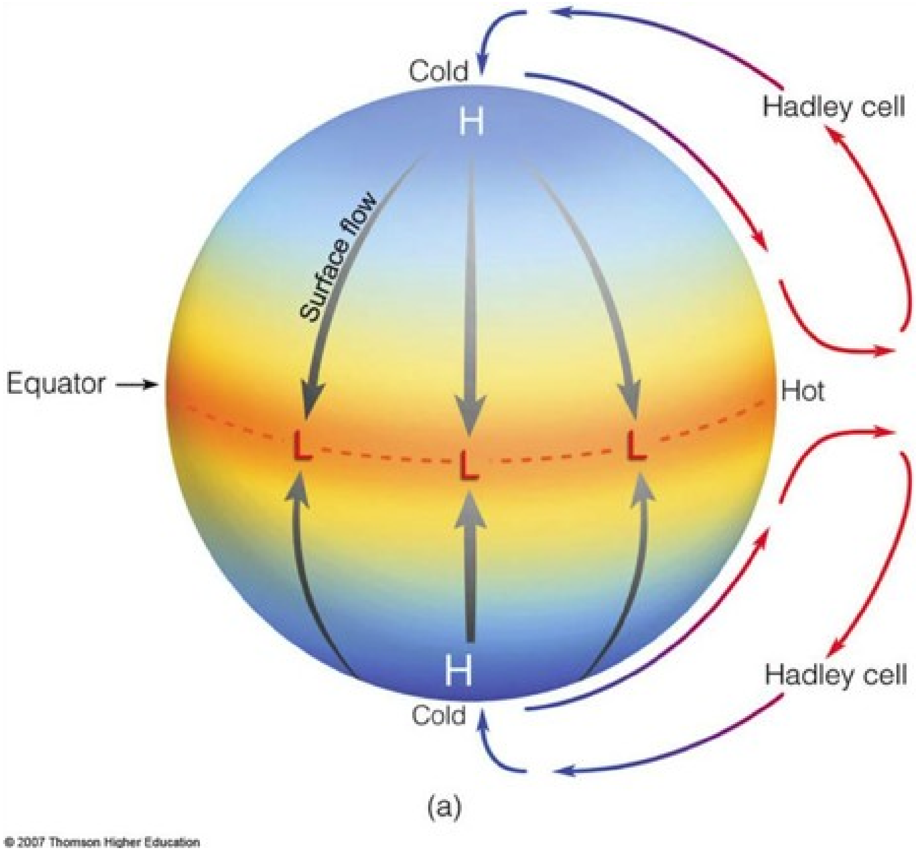






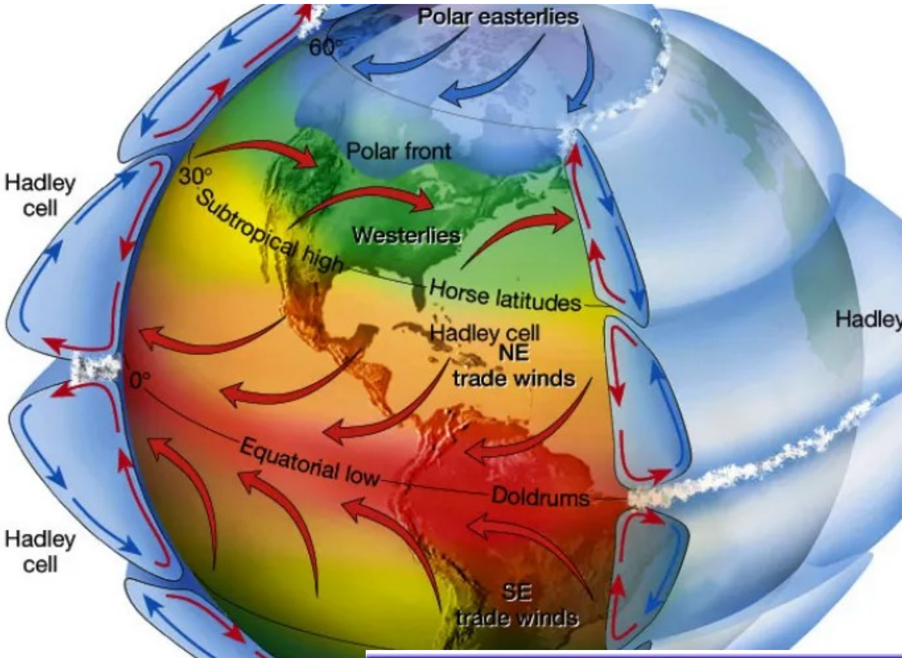
General circulation : Hadley cells

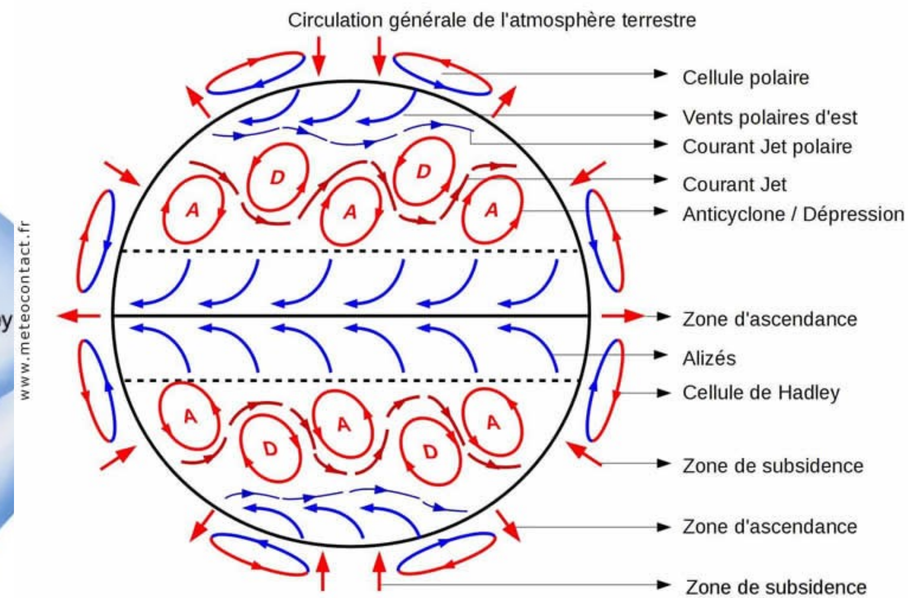
- Partial reequilibration with latitude from hot to cold

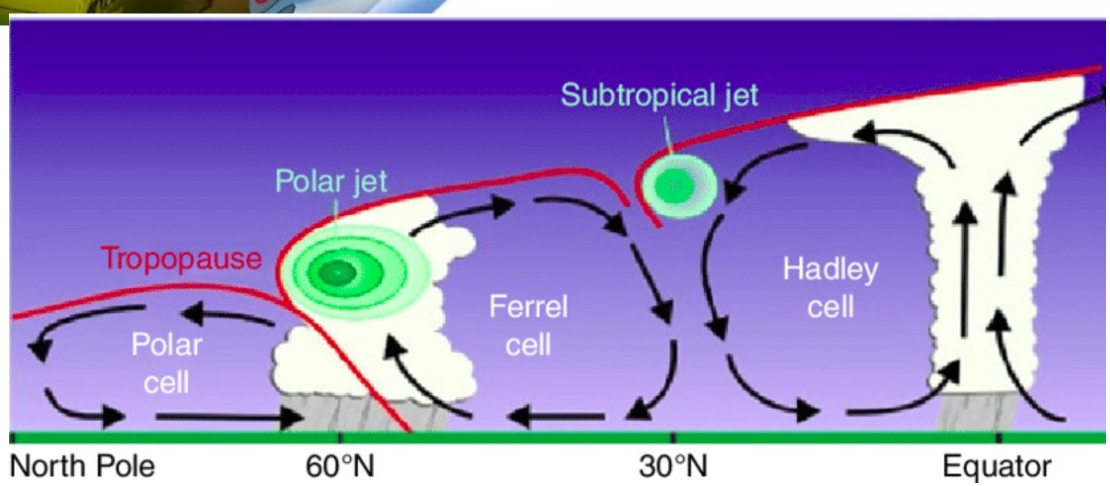


General circulation : Hadley cells

- Partial reequilibration with latitude from hot to cold
- Pattern structured by Coriolis force

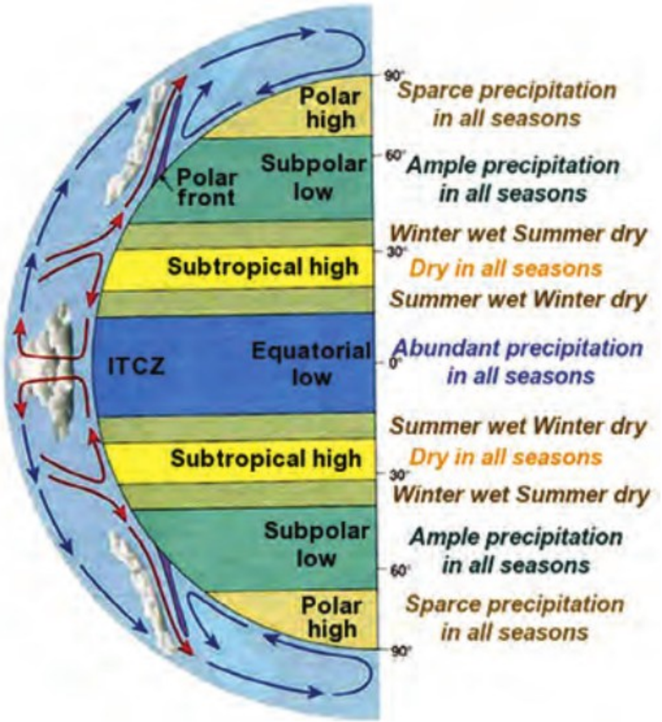


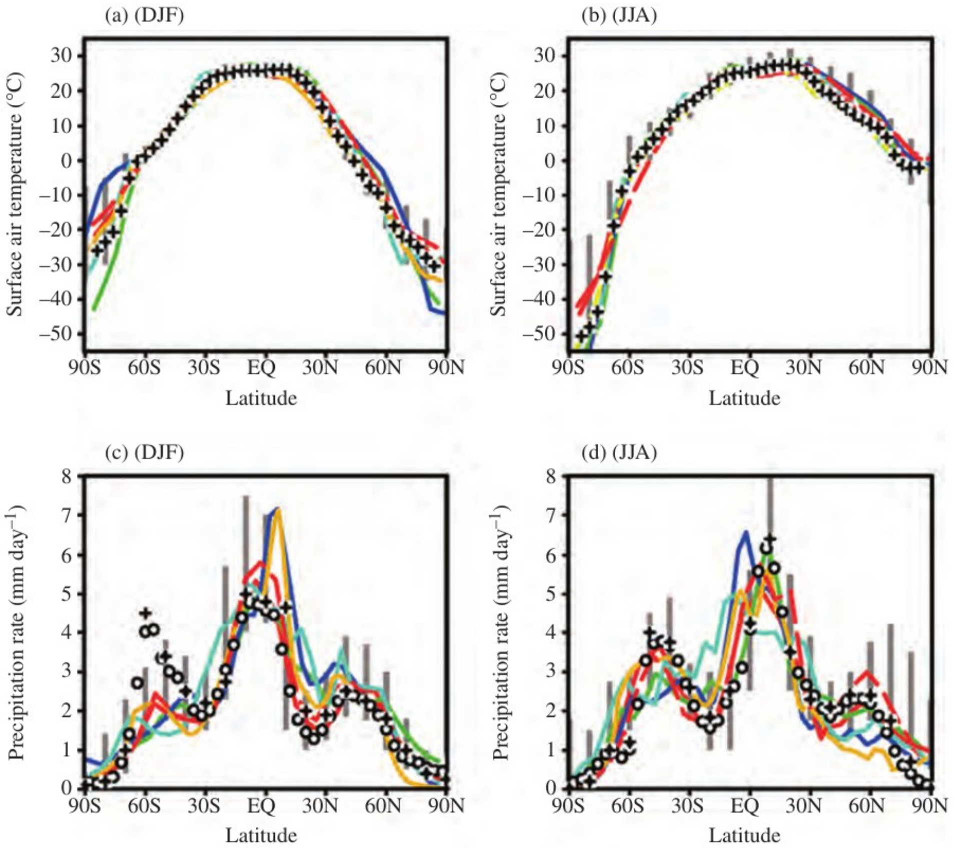




Zonal organisation of climate

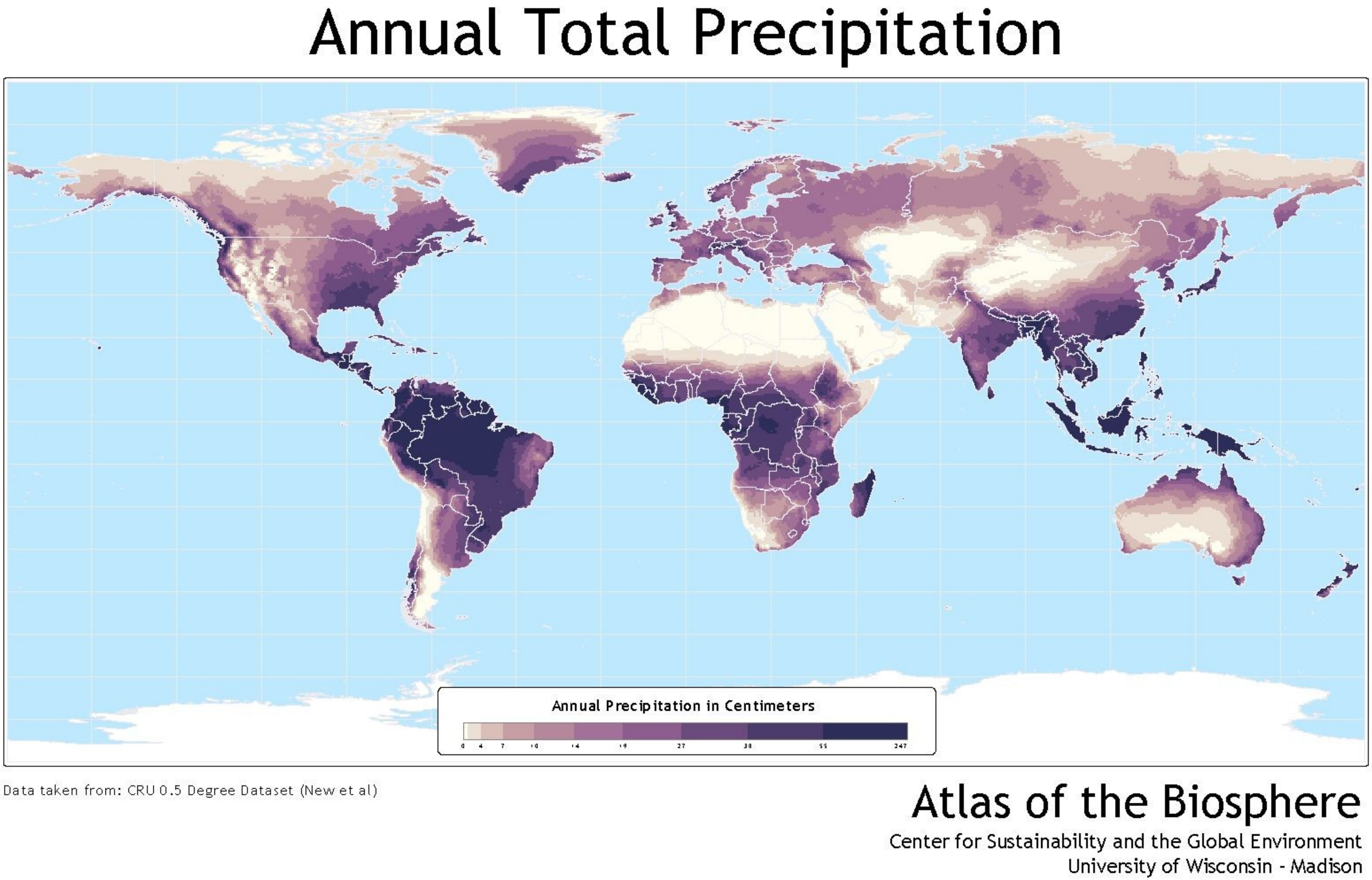
- Partial reequilibration with latitude





Zonal organisation of climate

- Partial reequilibration with latitude



Ocean role and structure

- Exchange of water / energy with the atmosphere through evaporation

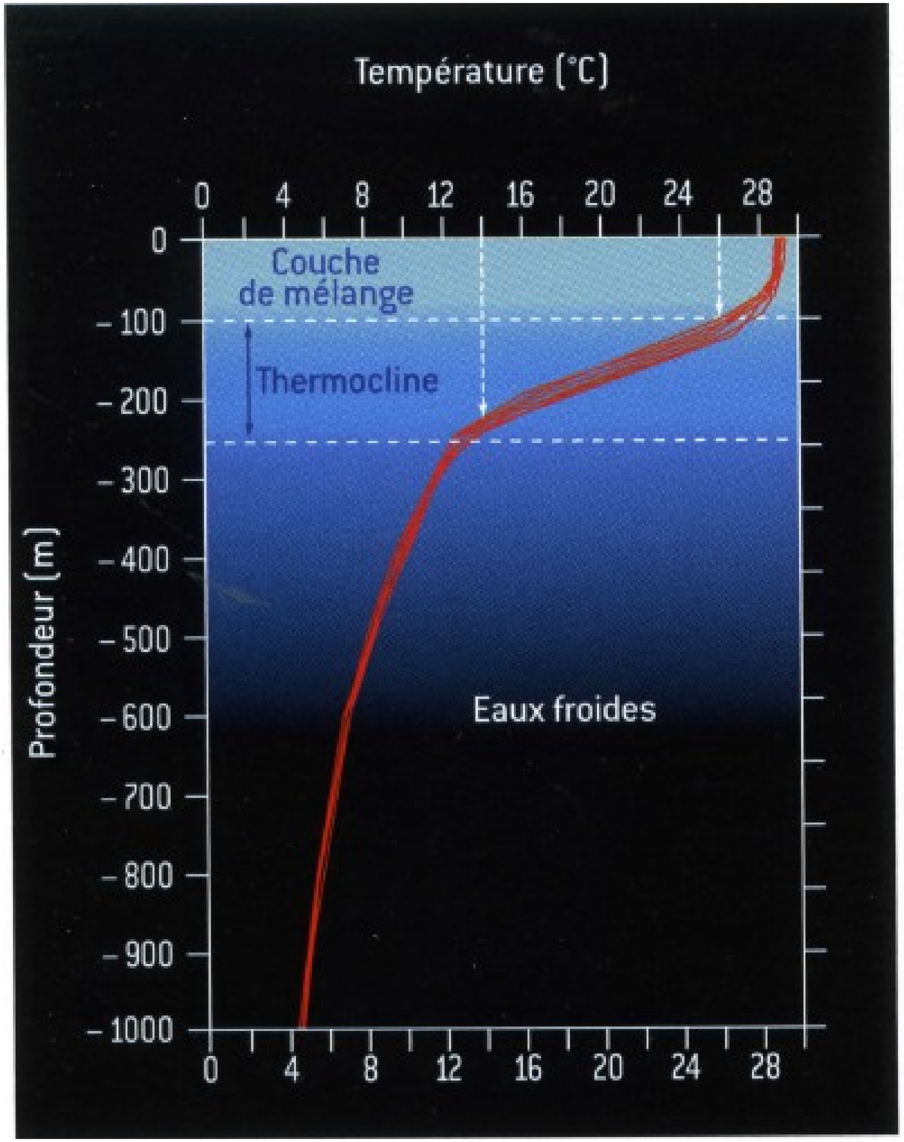
  Carries heat from equator to the poles

  Store heat

  Store and release CO_2

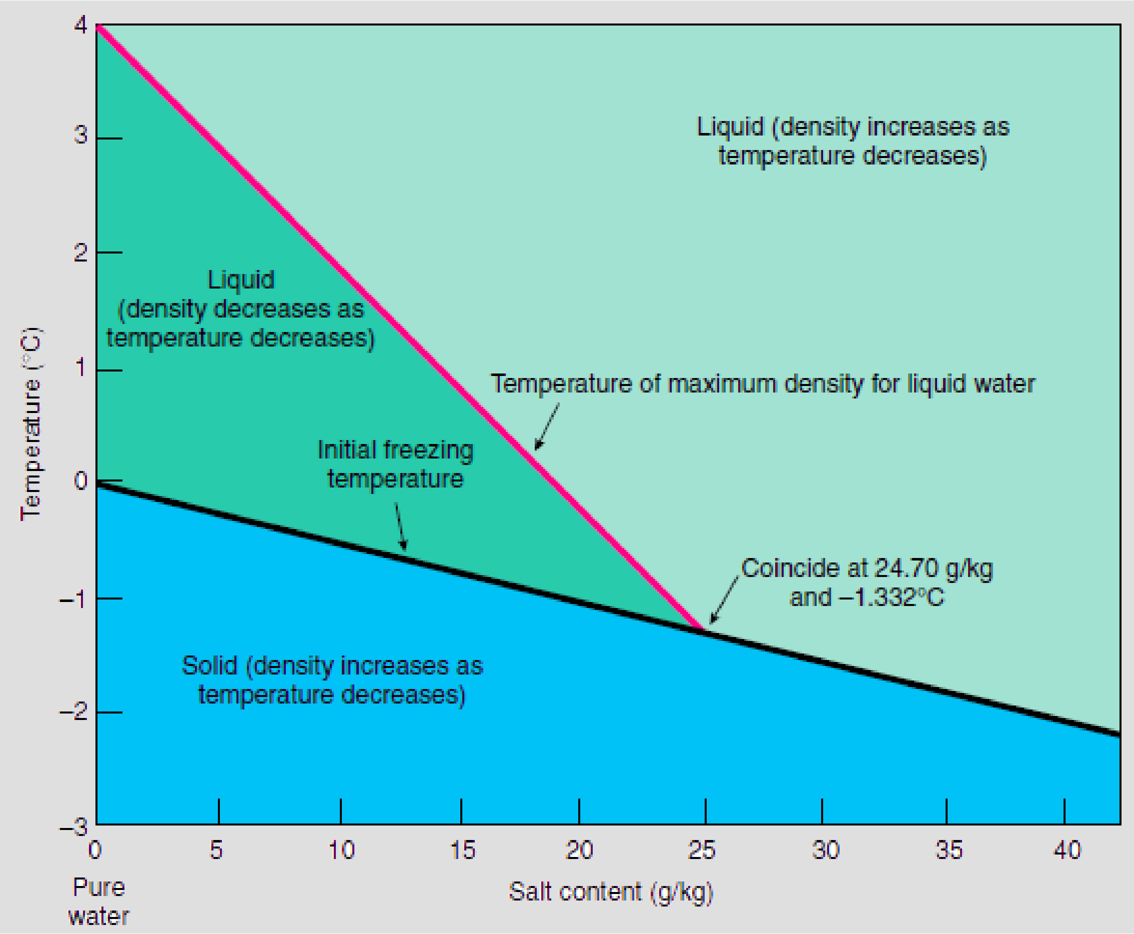
- Ocean is heated from above => very stable and stratified, little mixing or convection

- Horizontal currents flowing on surface (hot) or in depth (cold)



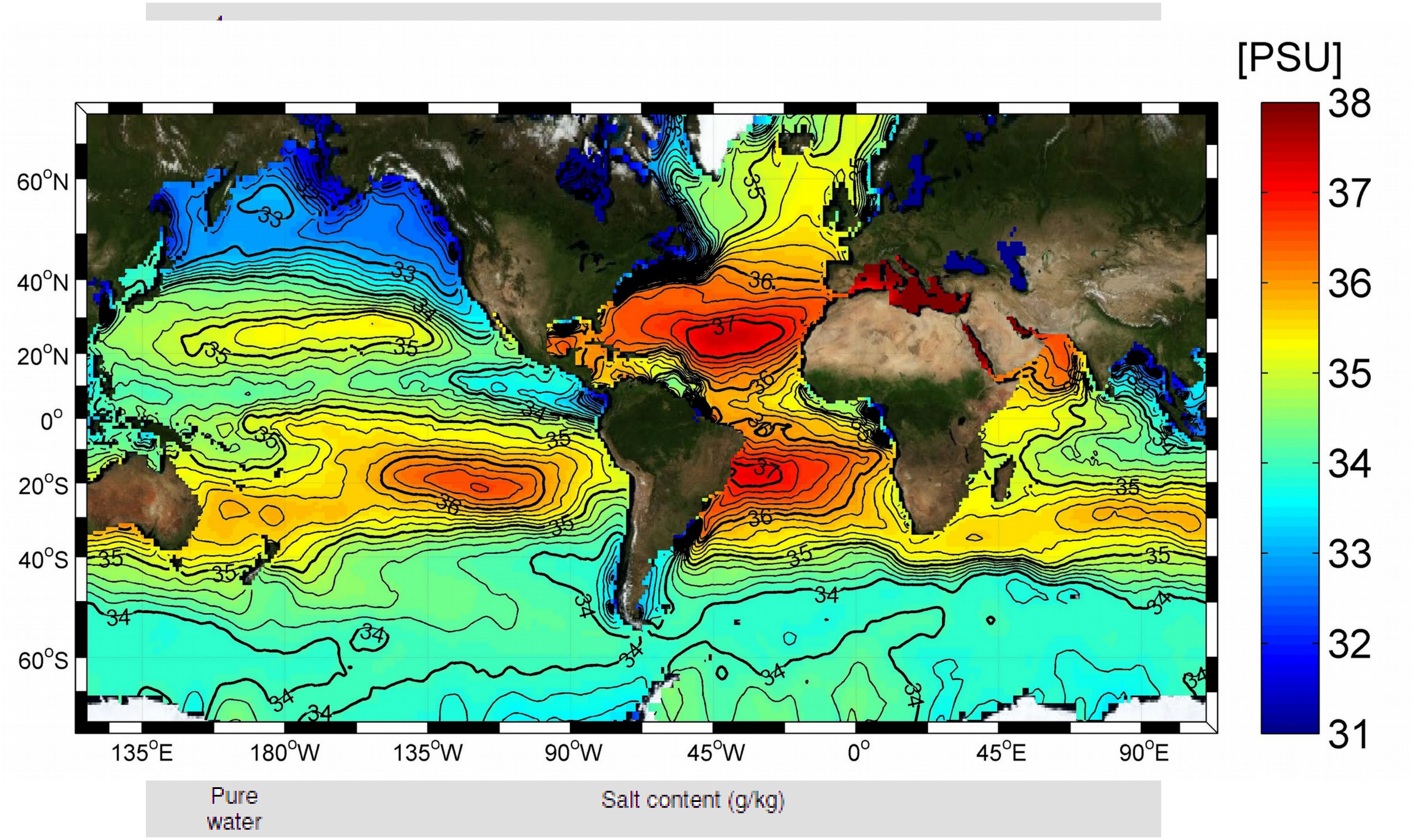
Density of water : salt and temperature

- Maximum of water density is around 4°C without salt
- Density increases with salt content
- Salinity is not uniformly distributed, it depends on the difference between evaporation and rainfall



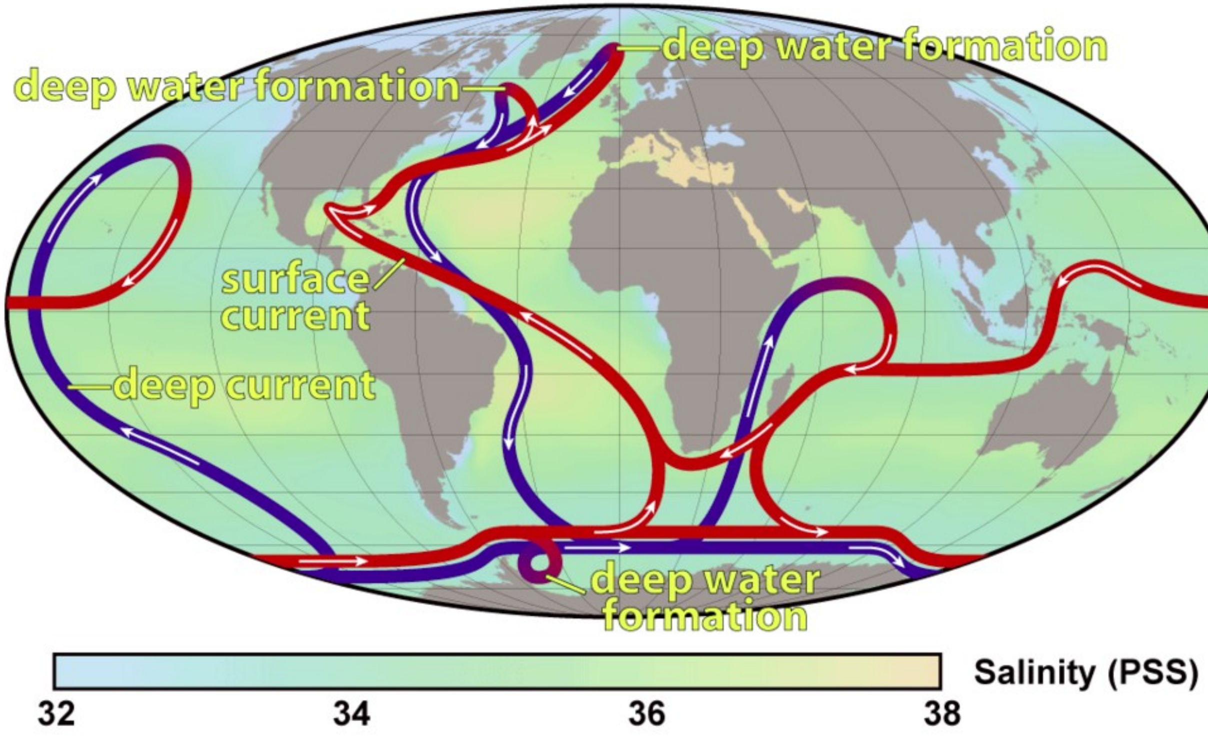
Density of water : salt and temperature

- Maximum of water density is around 4°C without salt
- Density increases with salt content
- Salinity is not uniformly distributed, it depends on the difference between evaporation and rainfall



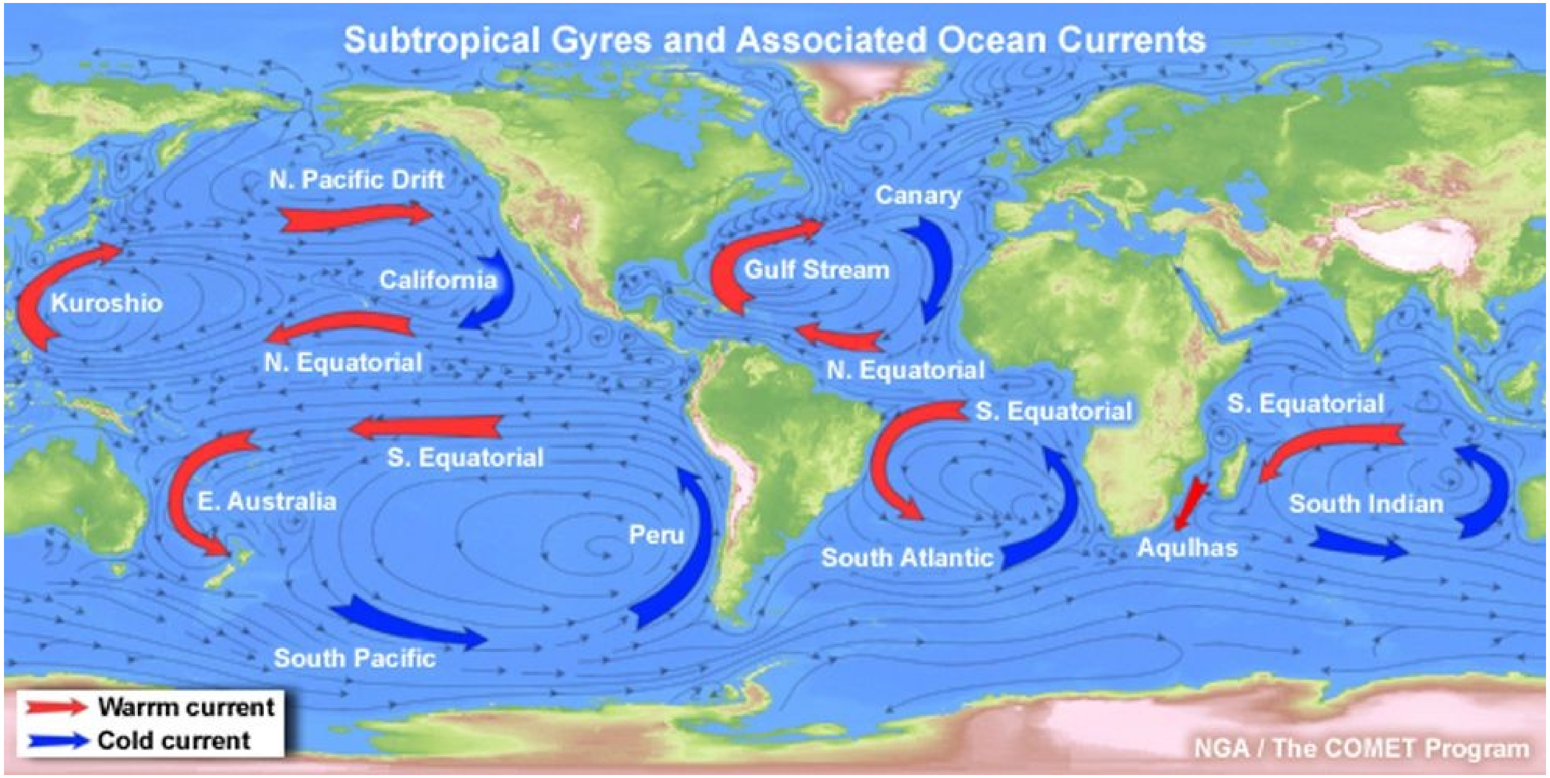
Ocean thermohaline circulation

- Surface currents are driven by wind over the first hundreds meter
- Deeper water currents loop the loop (~1000y for a molecule)
- When hot water goes to the poles, it cools down by evaporation, putting heat and water in the atmosphere, producing clouds
- Deepwater “forms” close to the poles when density from salty cooled water from surface sinks. Ice formation also increase saltiness.
- Currents are constraints by continents and ocean relief



Ocean surface currents

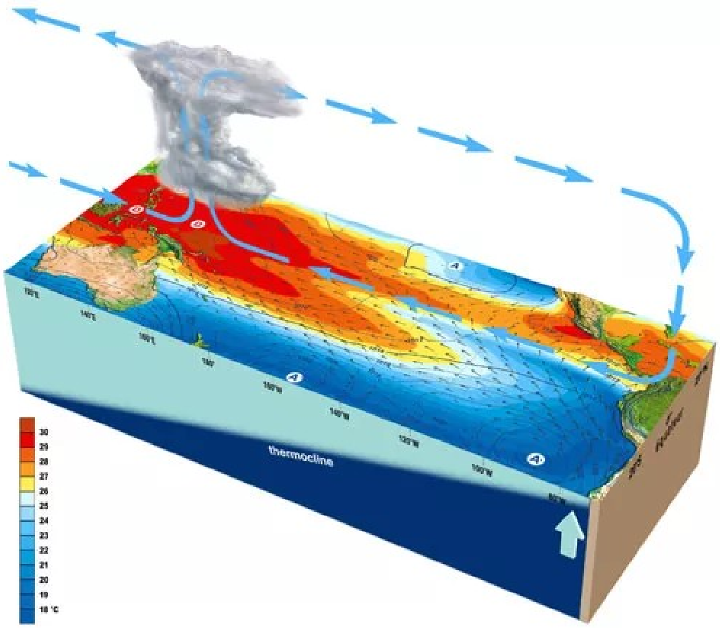
- Similar to anticyclone, surface currents organize into gyres due to Coriolis motion, geostrophic currents
- The “plastic continent” in northen pacific is stabilized by such large scale surface current

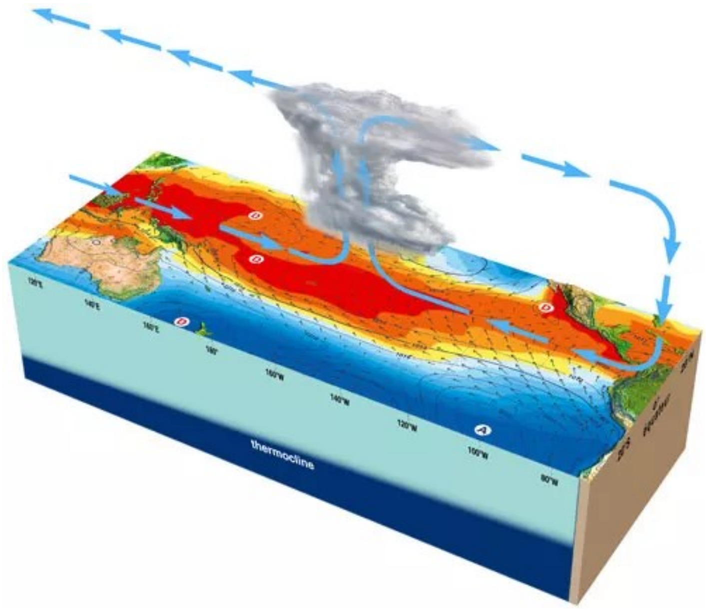


Regional oscillations between ocean and atmosphere

- Some regional mechanisms that occur on time scales between month and a few years that affect the climate on the global scale
- North atlantic oscillation
- No el Nino

El Nino

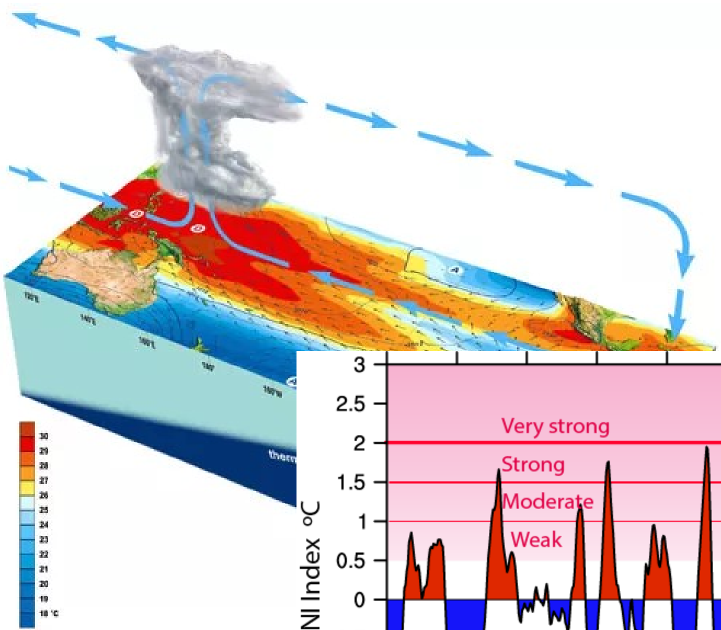


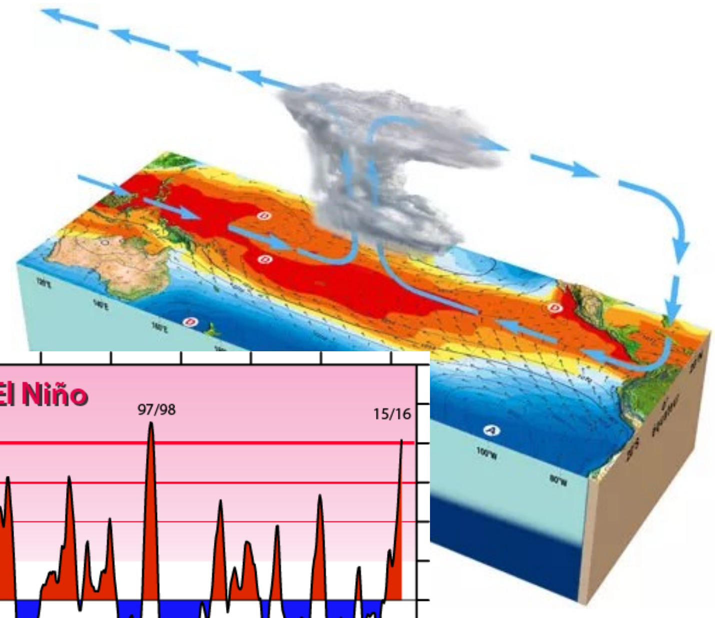


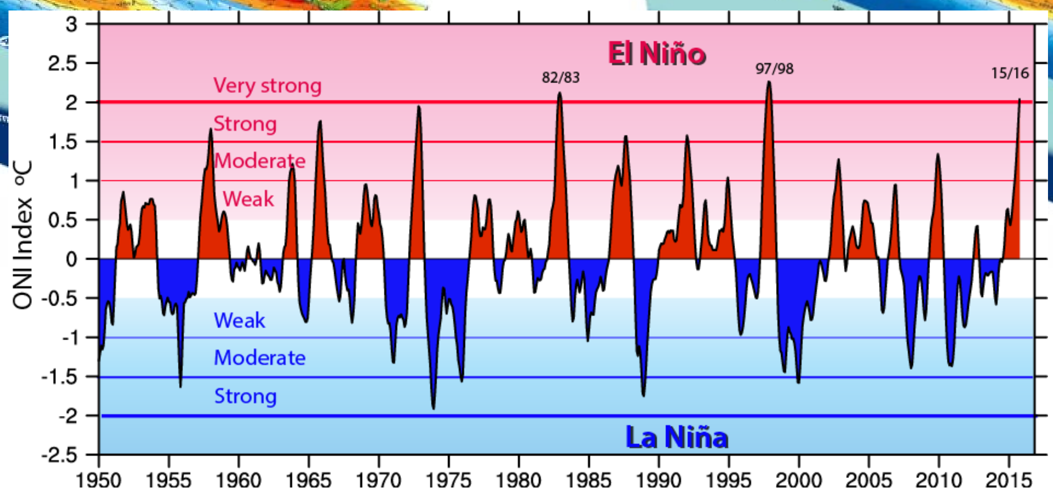
- Indian ocean dipole (responsible for fires in Australia)

Regional oscillations between ocean and atmosphere

- Some regional mechanisms that occur on time scales between month and a few years that affect the climate on the global scale
- North atlantic oscillation
- No el Nino　　　　　　　　　　El Nino







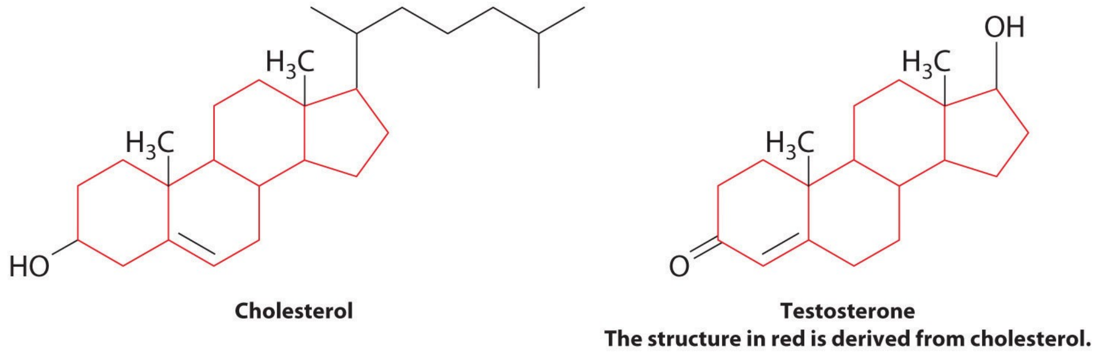
- Indian ocean dipole (responsible for fires in Australia)

Main cycles and anthropic perturbations

Elementary bricks of life

- Main atoms in the universe : H (90%), He (9%), O+C+Ne+N (0.13%)

- Life is based on C,H,O,N : thanks to the ability of carbon to create a diversity of robust and flexible bonds with a relatively low cost in energy to bind and unbind them
  => small molecules : H_2O, O_2, N_2, N20, CO, CO_2,…
  => organic material, big molecules and complex structure

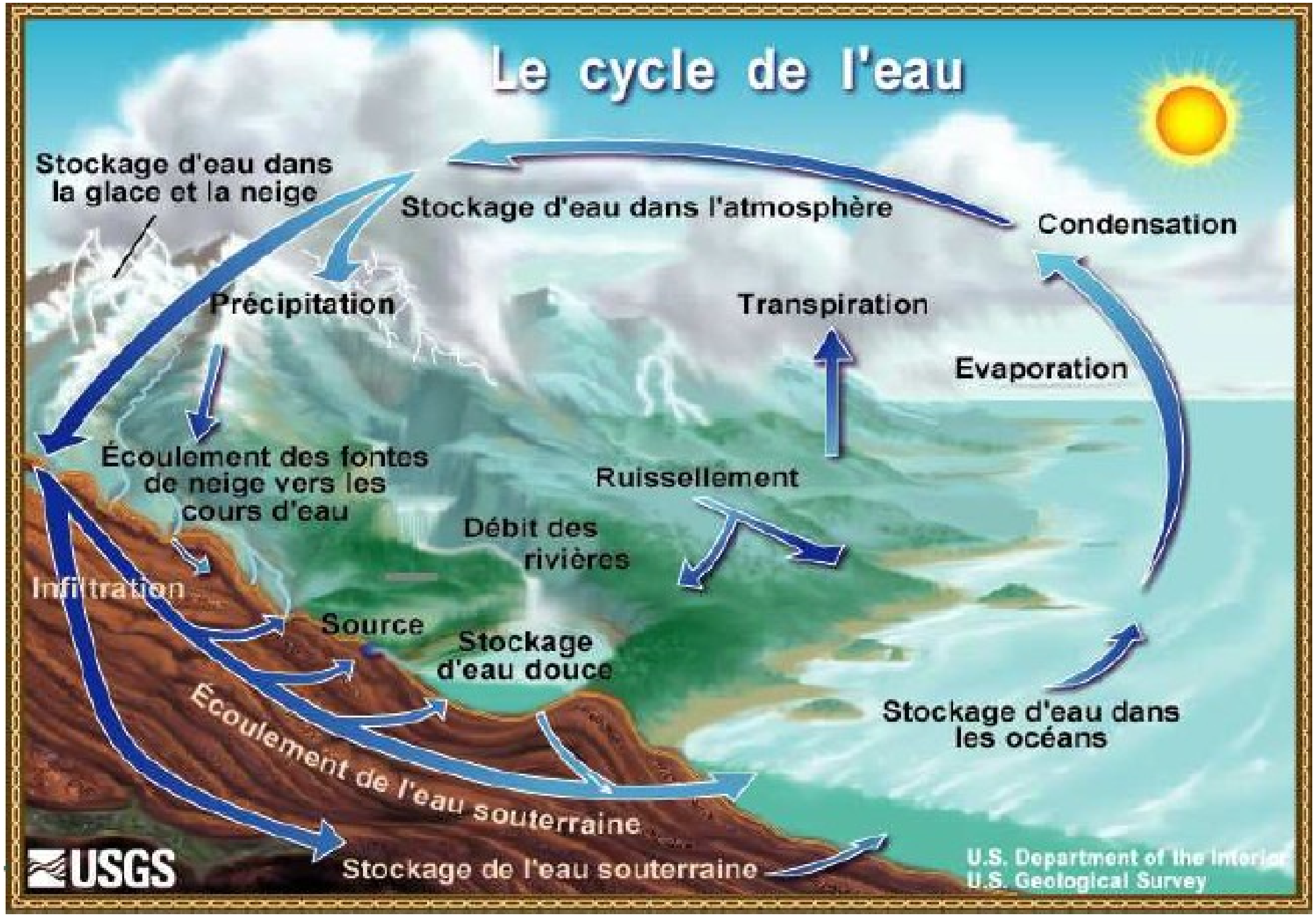


chemistry relies on and releases energy, obeys to thermodynamics

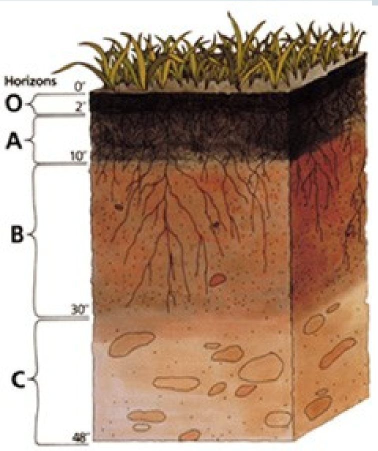
- Main cycles relevant for life and climate :
  water (H20), oxygen (O_2), ozone (O_3), carbon (C…), nitrogen (N…), phosphorus (P)

Water cycle

- Essential role in atmosphere and ocean, carries energy transfers through evaporation and condensation, dominant in greenhouse effect, role in biochemical cycles and weathering, for biomes...
- But not *directly* and significantly perturbed by human activities...

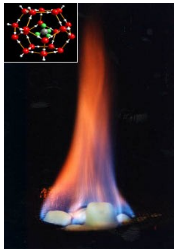


Carbon cycle : reservoirs



- Organic material in Biosphere : livings (animals, trees, planctons, bacterias,...) dead (oil, gas, coal => fossils!). Remark : soils contain a lot of carbon.

- CH_4 gas in atmosphere and solid hydrates in deep ocean, byproduct of decomposition of life and combustion.



- CO_2 gas in atmosphere and dissolved in the ocean $CO_3{}^{2-}$ $HCO_3{}^{-}$, byproduct of decomposition of life and combustion..

- Carbonate minerals : combination of the CO32− carbonate ion with minerals CaCO3 (calcite) CaMg(CO3)2 (dolomite) and many others salt, mostly present as sediments in the sea. Also the shells of many small animals

Carbon cycle : exchange processes

- Life energy cycle (storing the energy of sun in chemical bonds !)

$$6H_2O + 6CO_2 + \text{solar energy} \Rightarrow C_6H_{12}O_6\,(\text{glucose}) + 6O_2 \qquad (\text{photosynthesis})$$

$$C_6H_{12}O_6\,(\text{glucose}) + 6O_2 \Rightarrow 6H_2O + 6CO_2 + \text{energy} \qquad (\text{respiration})$$

- Anaerobic digestion (livestocks, waste) mediated by bacteria

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$$

- Alcolic fermentation

$$C_6H_{12}O_6 \rightarrow 2\ C_2H_5OH + 2\ CO_2$$

- Combustion of organic based compound

$$\underset{\substack{\text{propane}\\(\text{fuel})}}{C_3H_8} + \underset{\text{oxygen}}{5\,O_2} \longrightarrow \underset{\text{carbon dioxide}}{3\,CO_2} + \underset{\text{water}}{4\,H_2O}$$

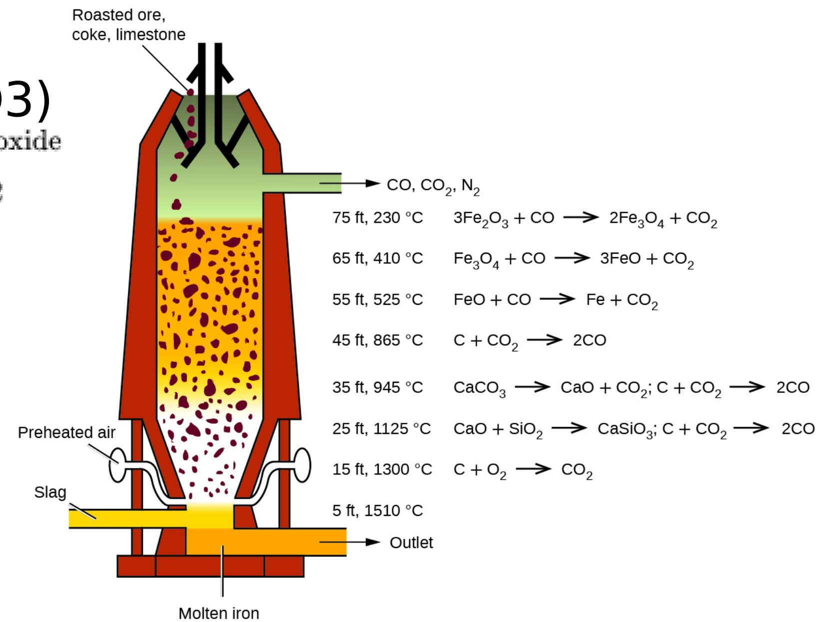
- Lime (Cement is close to that 3CaO·Al2O3)

$$\overset{\text{calcium carbonate}}{CaCO_3} \xrightarrow[\text{heat}]{} \overset{\text{calcium oxide}}{CaO} + \overset{\text{carbon dioxide}}{CO_2}$$

- Steel

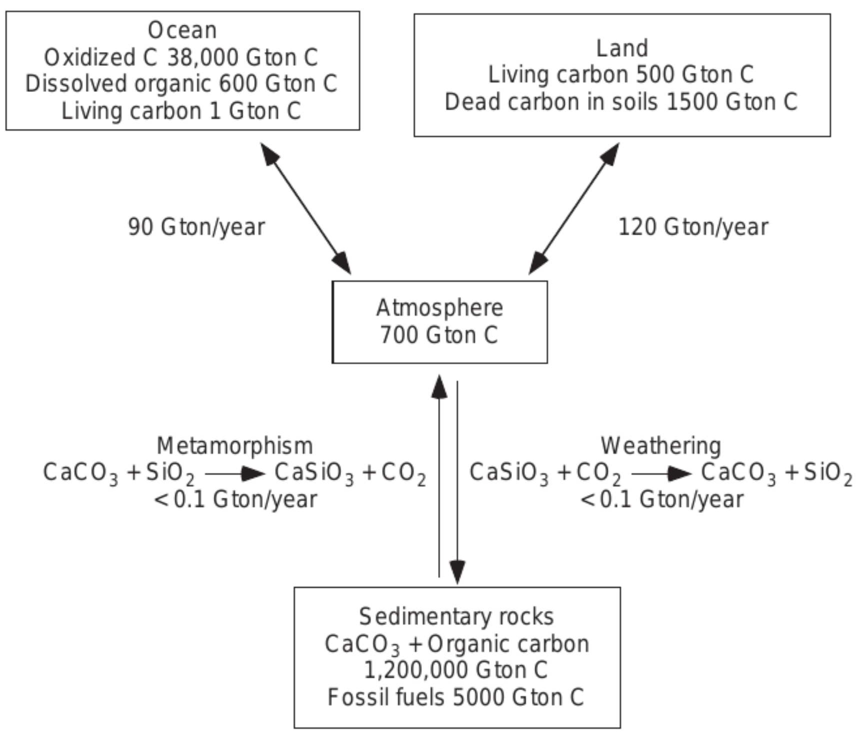
$$Fe2O3(s) + 3C(s) \rightarrow 2Fe(l) + 3CO(g)$$

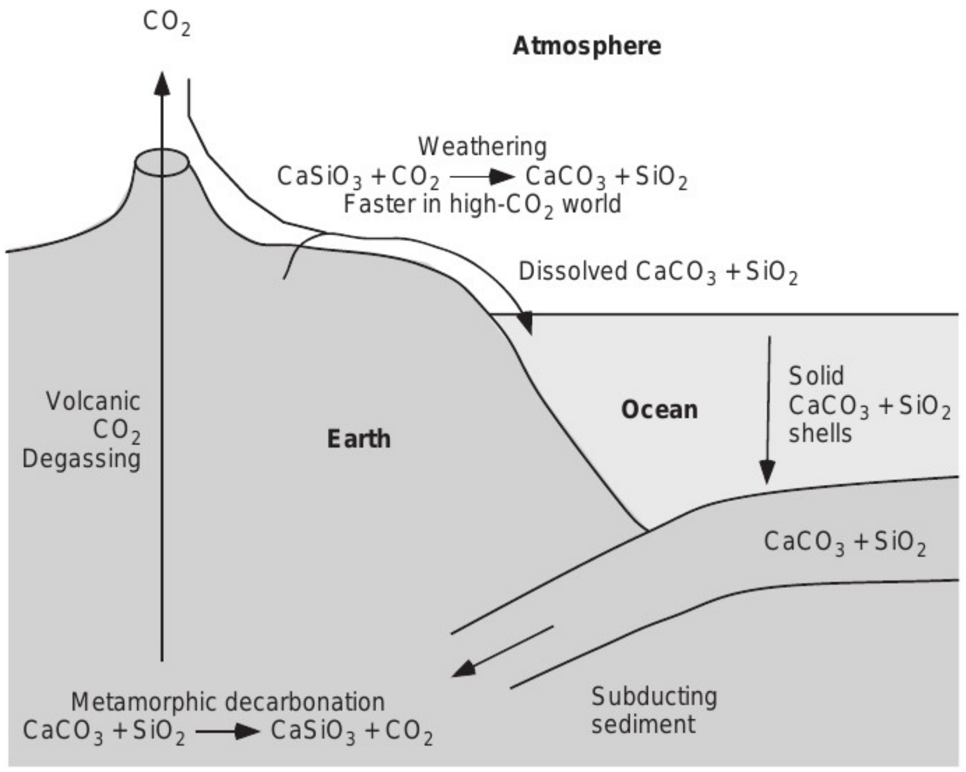
- Many others...



Carbon cycle : the sedimentary part

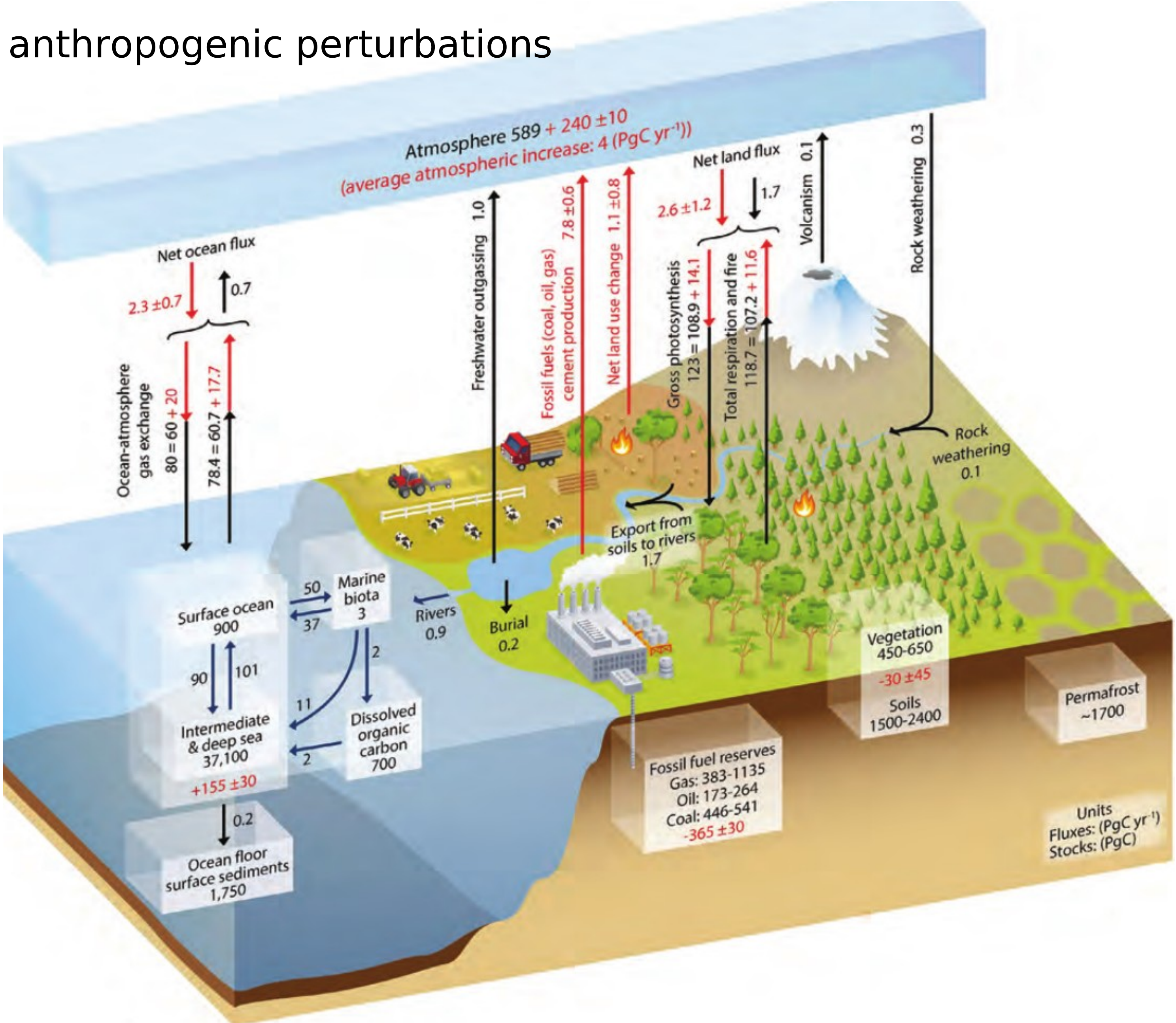
- Huge reservoir but very slow





Carbon cycle : summary

- In red : anthropogenic perturbations



« The smoking gun »

global emission CO_2

36 Gt / year

conversion factor

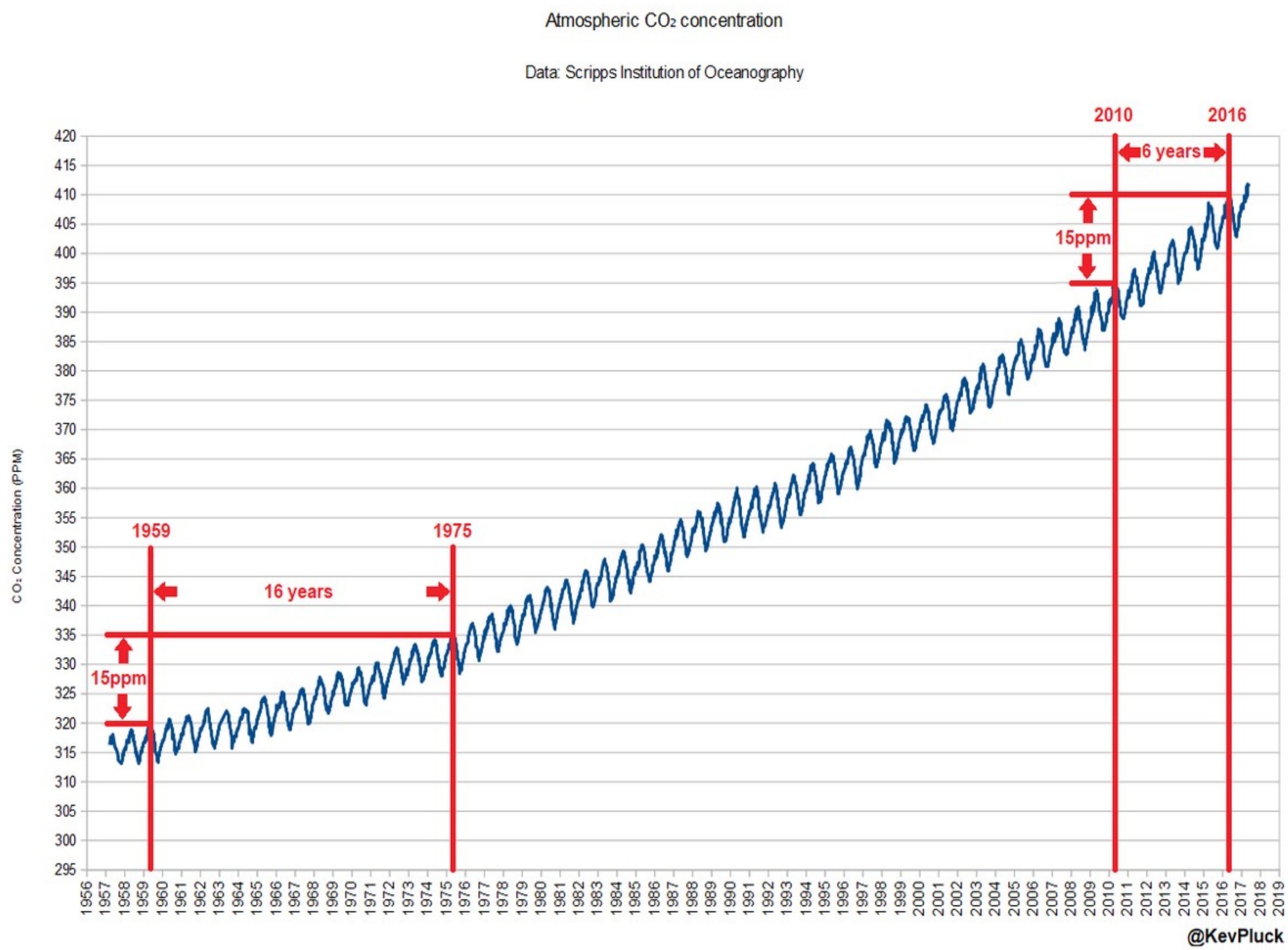
7.3 Gt = 1 ppm

should give

5 ppm / an

observation

2.5 ppm / an

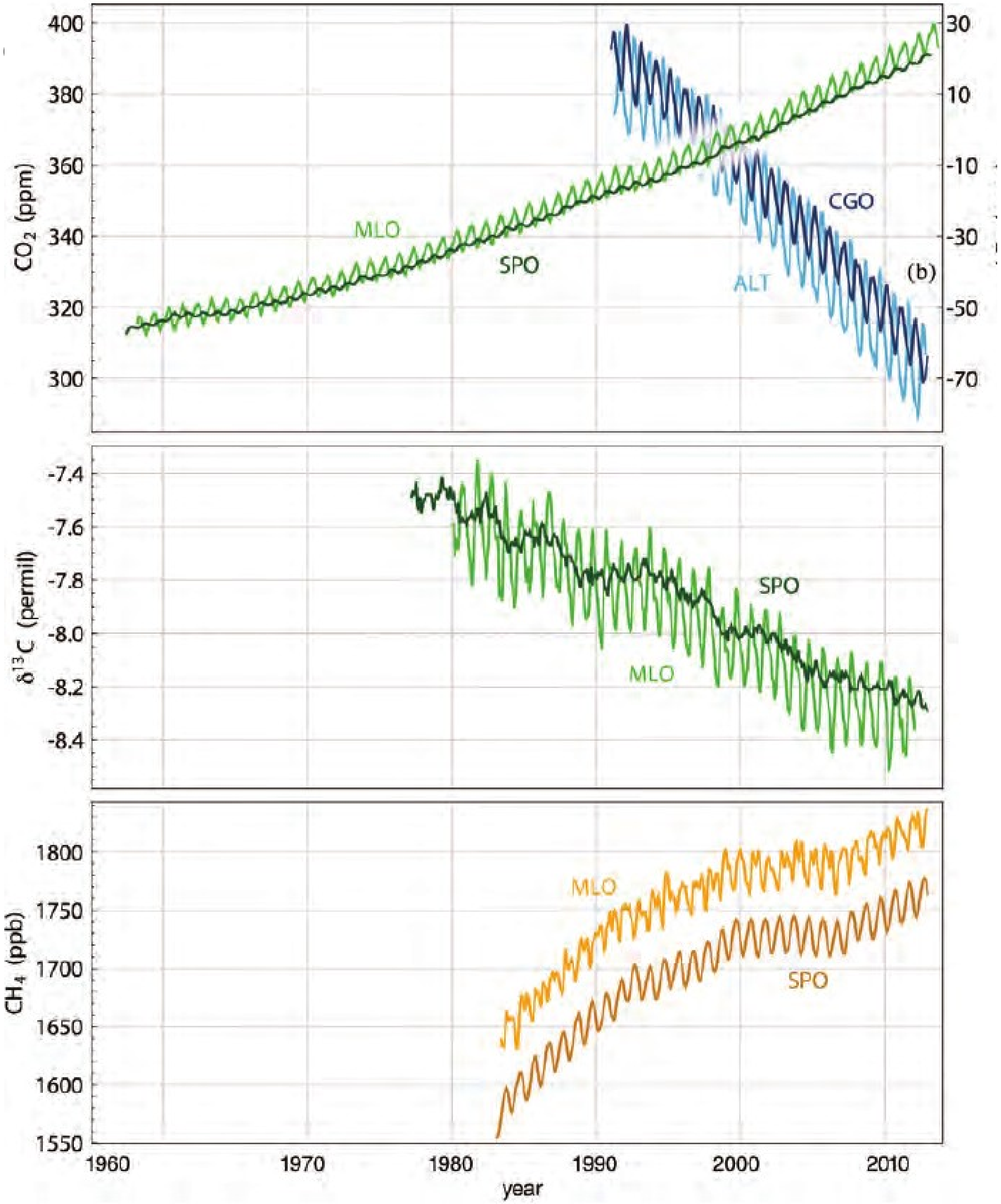


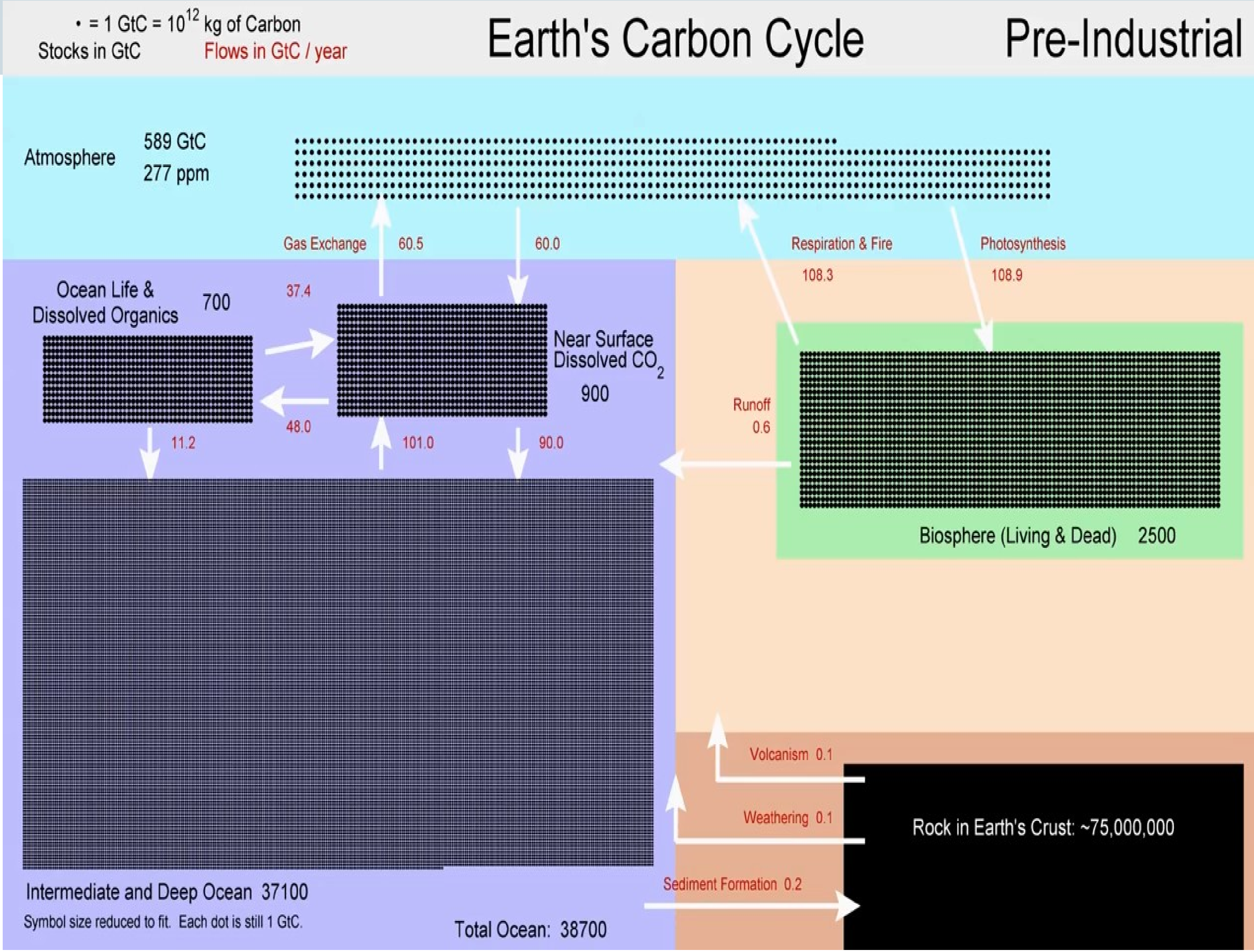
Probing the anthropic origin

Decrease of oxygen associate to combustion

decrease of isotope

increase of methane

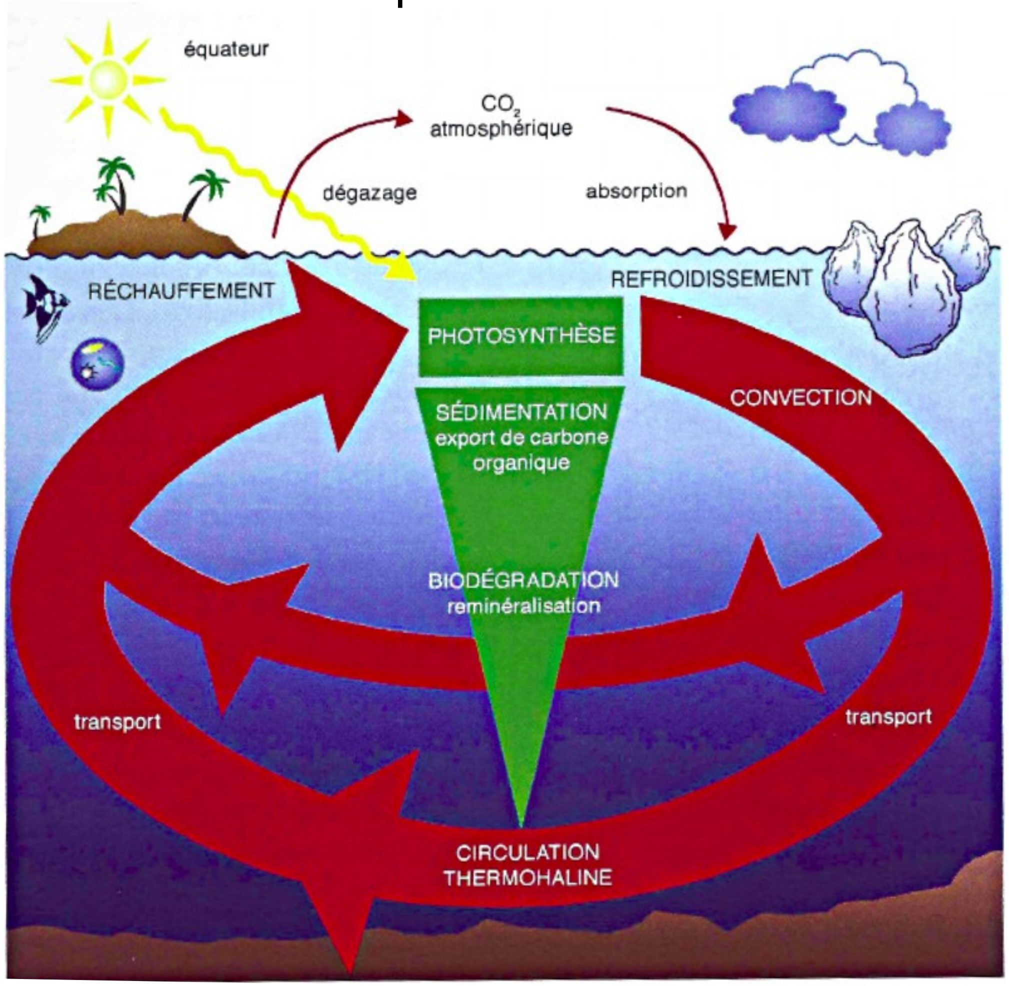




• = 1 GtC = 10^{12} kg of Carbon
Stocks in GtC
Flows in GtC / year
Earth's Carbon Cycle
Pre-Industrial
Atmosphere
589 GtC
277 ppm
Gas Exchange
60.5
60.0
Respiration & Fire
108.3
Photosynthesis
108.9
Ocean Life & Dissolved Organics
700
37.4
Near Surface Dissolved CO_2
900
48.0
11.2
101.0
90.0
Runoff
0.6
Biosphere (Living & Dead) 2500
Volcanism 0.1
Weathering 0.1
Rock in Earth's Crust: ~75,000,000
Sediment Formation 0.2
Intermediate and Deep Ocean 37100
Symbol size reduced to fit. Each dot is still 1 GtC.
Total Ocean: 38700

Coupling with ocean circulation

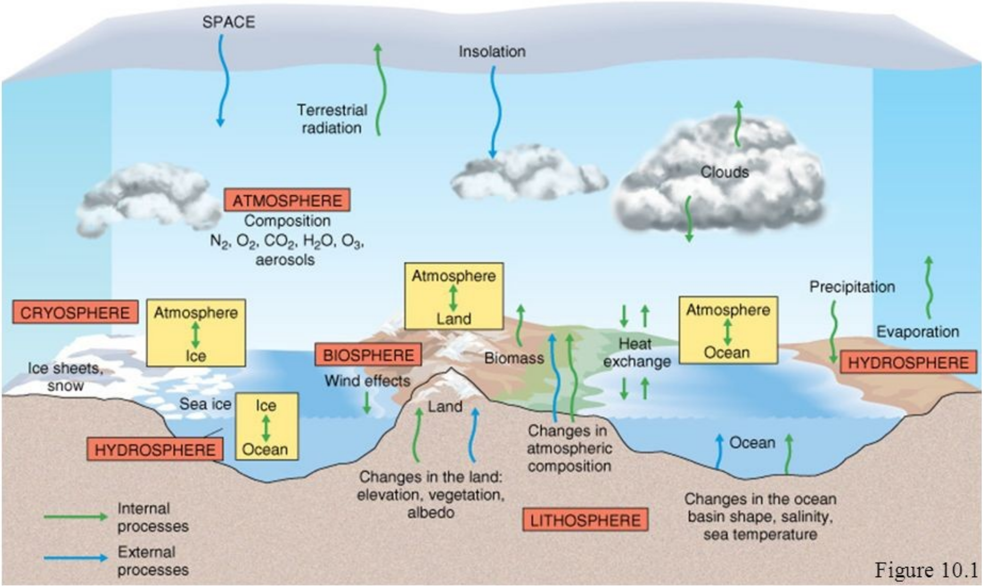
- Currently, ~30% of extra CO2 from human activity is partially dissolved in surface oceans and buried into deep water through thermohaline circulation.
- Biochemical cycles are also coupled with each others...

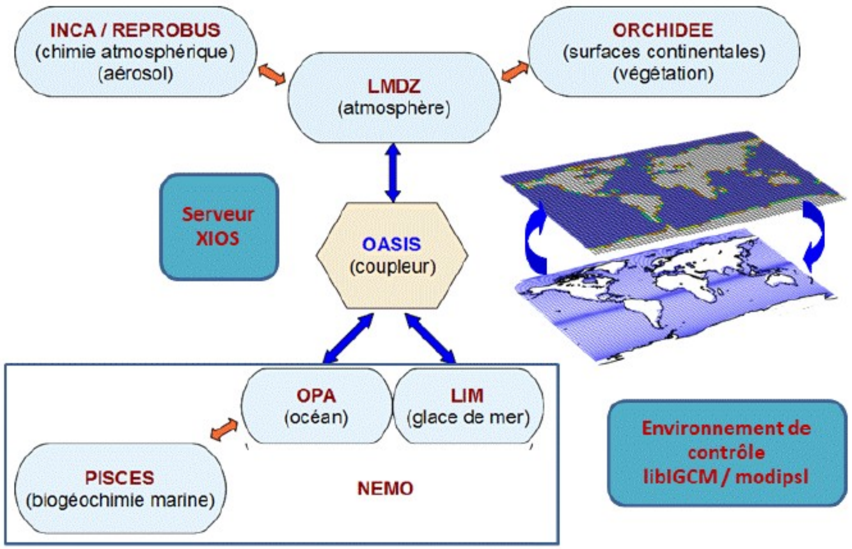


Climate modeling and predictions

Climate models

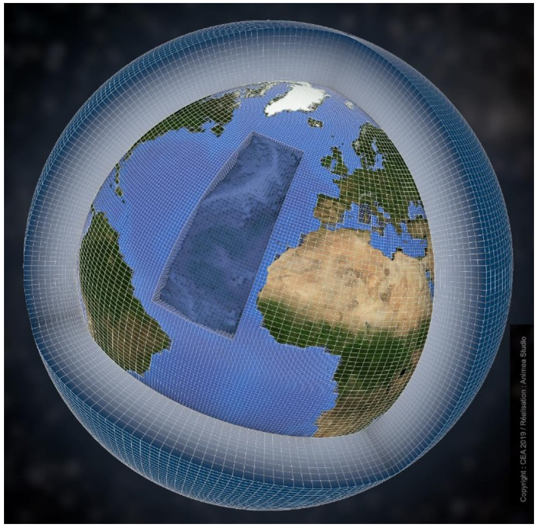
- Many components => Earth system (example of CMIP6 @IPSL 2019)
  Transient response, dynamical simulations

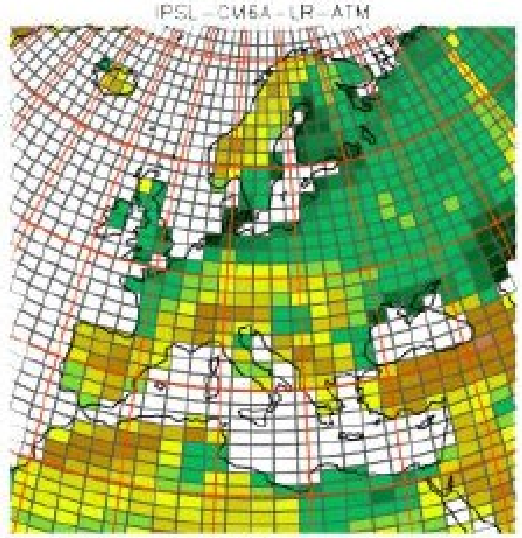




- Numerical implementation

  => movie
  CEA movie on modelling climate





Radiative forcing and feedbacks

- Radiative forcing : “Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. In this report radiative forcing values are for changes relative to preindustrial conditions defined at 1750 and are expressed in Watts per square meter (W/m2). “

- Radiative balance at the top of the troposphere : $N(\vec{E}, \vec{I}, T_s) = \mathcal{F}'_s - \Phi_{\mathrm{out}}$
- Elementary variation :

$$\Delta N = \underbrace{\sum_i \frac{\partial N}{\partial E_i} \Delta E_i}_{\text{forcing}} + \underbrace{\left(\frac{\partial N}{\partial T_s} + \sum_j \frac{\partial N}{\partial I_j} \frac{\partial I_j}{\partial T_s} \right)}_{\text{response}} \Delta T_s$$

- Total radiative forcing : $\Delta F = \sum_i \Delta F_i$

- Bare gain : $G_0^{-1} = -\frac{\partial N}{\partial T_s}$ Retroaction term : $R = \sum_j \frac{\partial N}{\partial I_j} \frac{\partial I_j}{\partial T_s}$

- Change in temperature : $\Delta T_s = \frac{G_0}{1 - RG_0} \Delta F$

R>0 : positive feedback
R<0 : negative feedback

Examples of feedbacks and inertia

- Positive

  water vapor concentration (increasing saturation pressure)
  ice albedo
  cirrus (high clouds) via greenhouse dominant effect
  El Nino
  permafrost melting

- Negative

  change in atmosphere temperature profile

  stratus (low clouds) via albedo dominant effects
  sulfate aerosol indirect effect (favors clouds)

- Thermal inertia (introducing the specific heat of the system):

$$C_s \frac{\mathrm{d}\Delta T_s}{\mathrm{d}t} = \Delta N = \Delta F - G^{-1}\Delta T_s \quad \Rightarrow \quad \Delta T_s(t) = \Delta T_s^{\mathbf{eq}}(1 - e^{t/\tau})$$

  response time : $\tau = GC_s$

Climate sensitivity

- Equilibrium response after doubling of CO_2 concentration with respect to pre-industrial concentration.

$$\Delta T_s^{\mathbf{eq}} = \lambda \Delta F$$

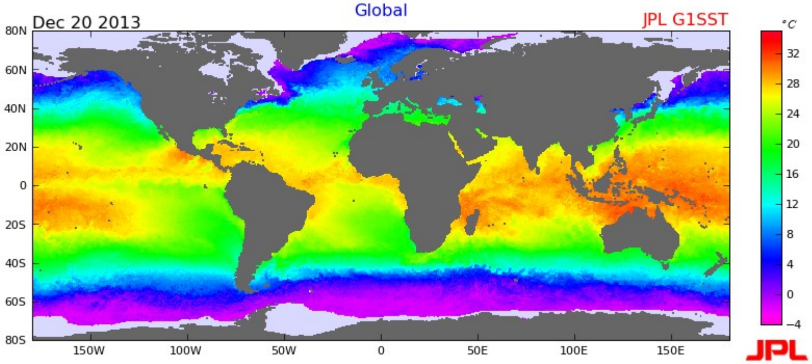
- Transient response : increase CO_2 concentration by 1% during 70 years to reach doubling of concentration. System is not equilibrated at the end of the simulation

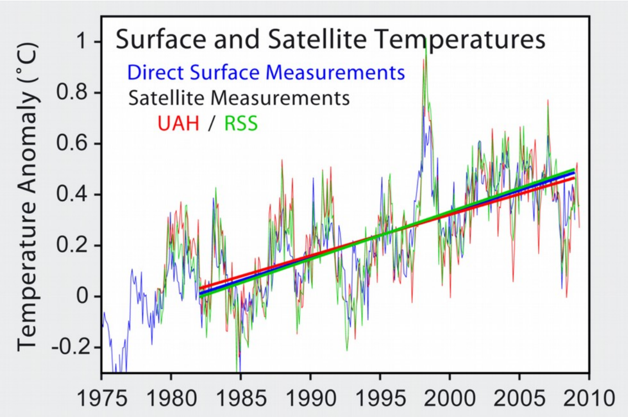
- From 2019 results

	CMIP5		CMIP6	
Modèle	Réponse à l'équilibre	Réponse transitoire	Réponse à l'équilibre	Réponse transitoire
IPSL-CM5A-LR	4,1 °C	2,0 °C	4,8 °C	2,4 °C
CNRM-CM6-1	3,3 °C	2,1 °C	4,9 °C	2,0 °C

Measuring the global temperature

- Meteorological stations and buoys (sea surface temperature on oceans, 2m above ground on continent)
- Weather balloon radiosonde
- Satellite measurement : from radiometric measurements (visible, infrared and microwaves bands) at various altitudes, calibration and correction are necessary => but global !





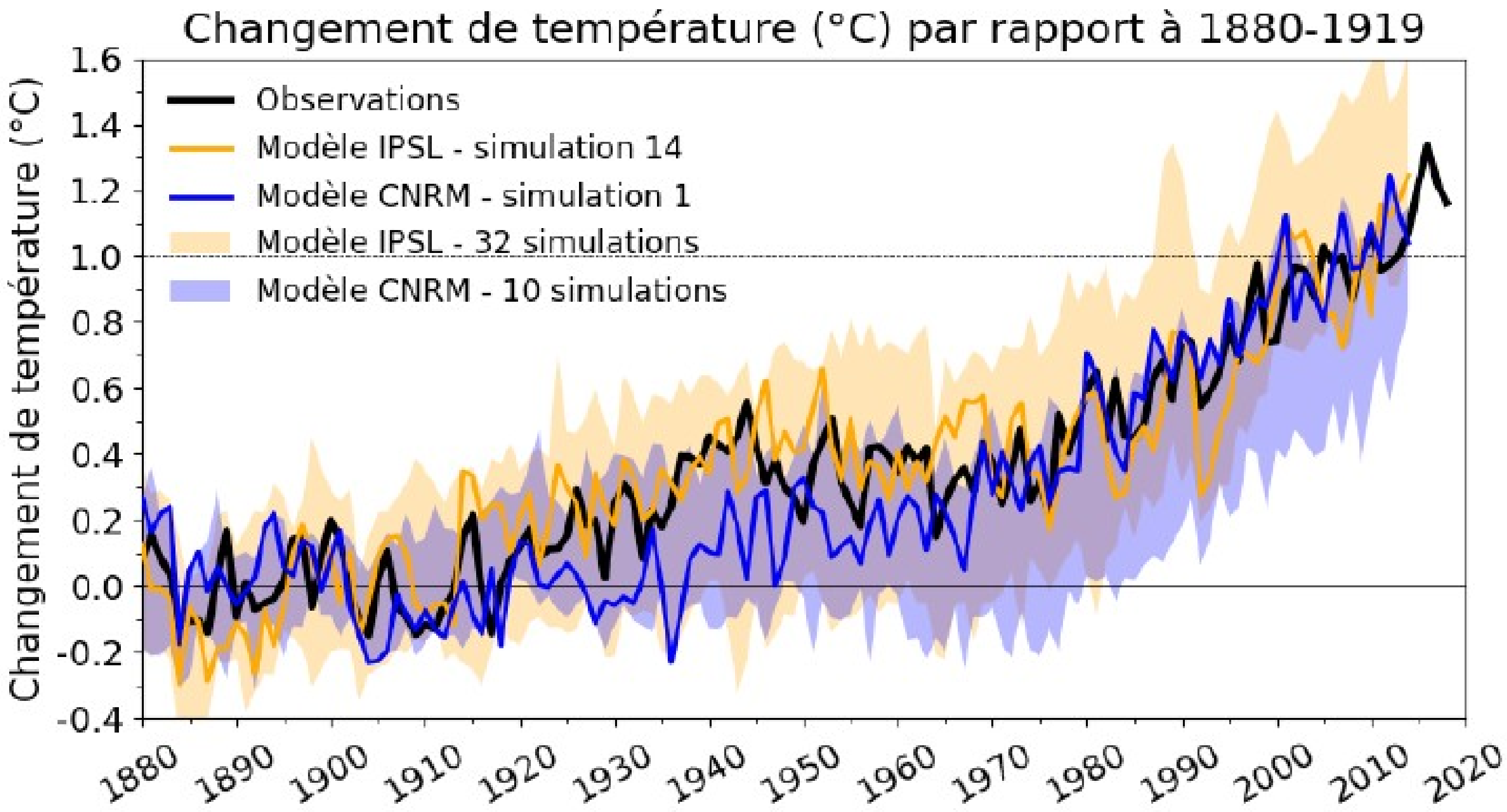
- Global temperature reconstructed by Climatid Research Unit (University of East Anglia, UK) : data science techniques and statistical analysis to homogeneize data, to look for biais from apparatus changes, spatial reconstruction, reanalysis confronting with other physical parameters and confrontation with numerical models (for data since 1979) .
- What matters most to follow global warming is the relative increase of temperature which is easier to get than the absolute mean temperature. => this is called the temperature anomaly

Principles and benchmarking models

- Various initial conditions because the initial state in 1880 is not known with precision (the rest is fixed afterwards)

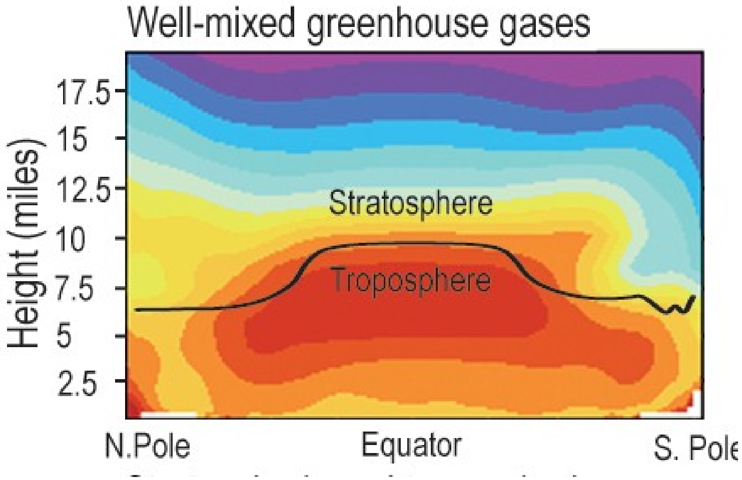
Principles and benchmarking models

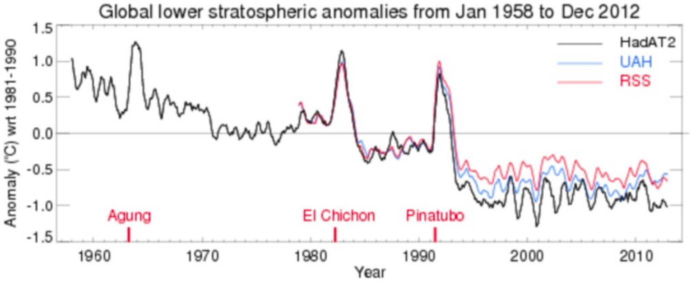
- Various initial conditions because the initial state in 1880 is not known with precision (the rest is fixed afterwards)

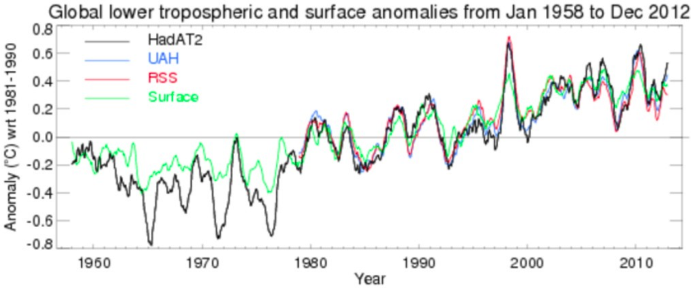


Probing the anthropic origin of warming

Cooling of the stratosphere

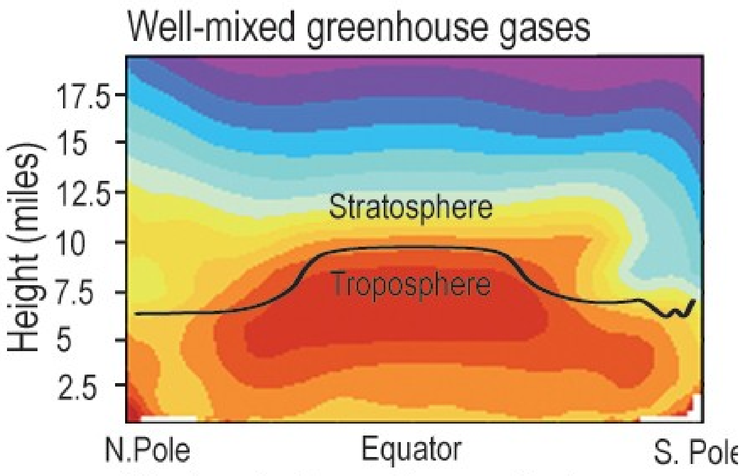


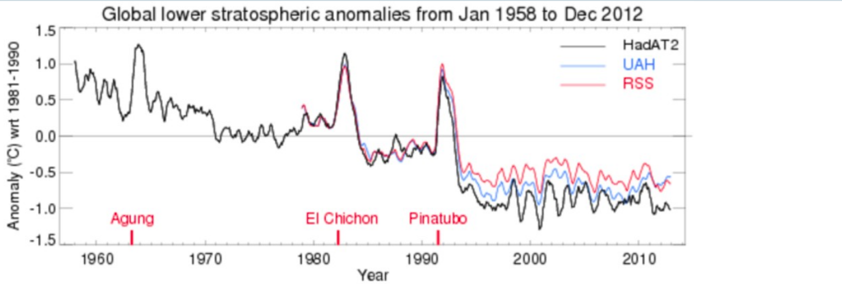


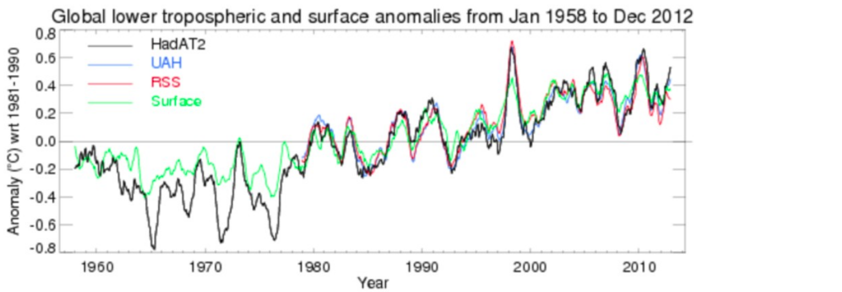


Probing the anthropic origin of warming

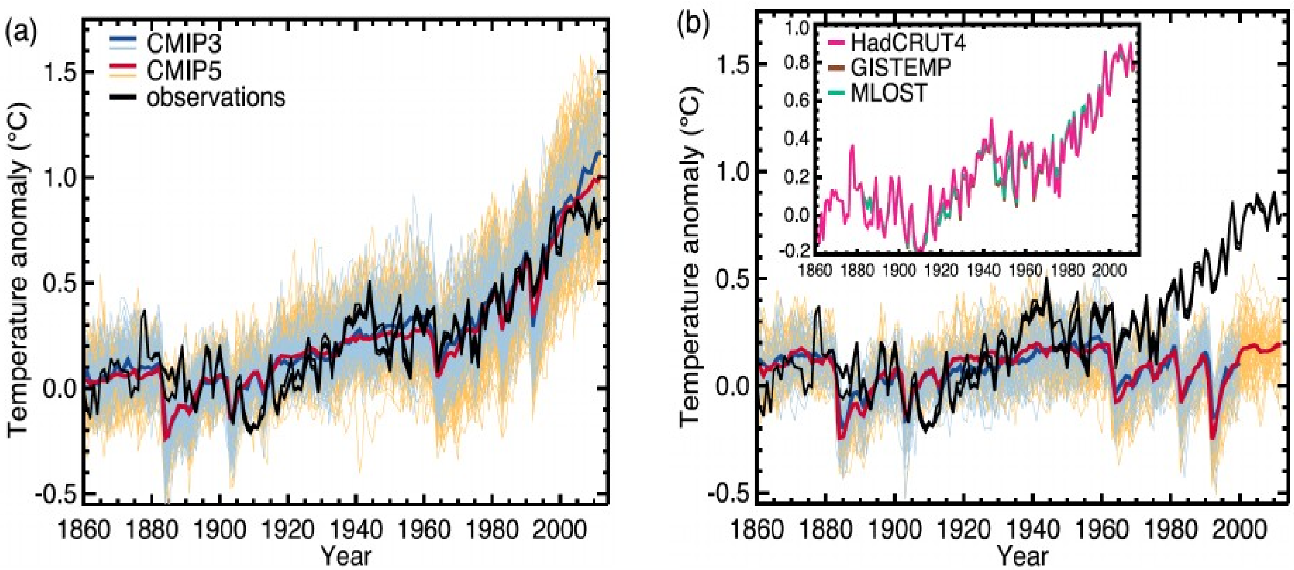
Cooling of the stratosphere





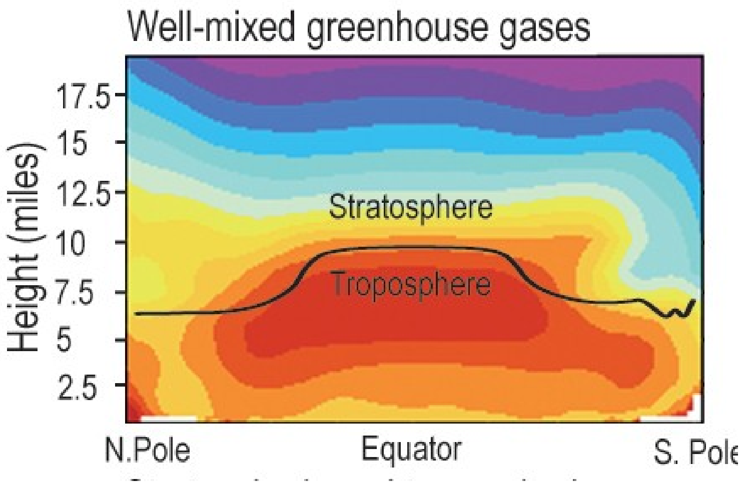


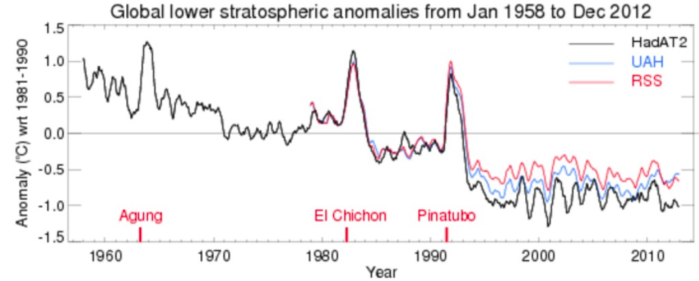
Estimating radiative forcing components (IPCC 2014) => **1.5 *W/m²***

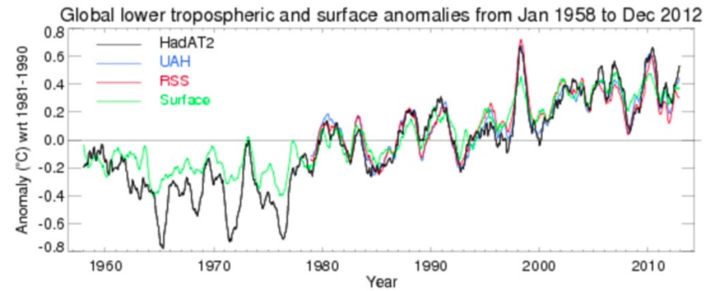


Probing the anthropic origin of warming

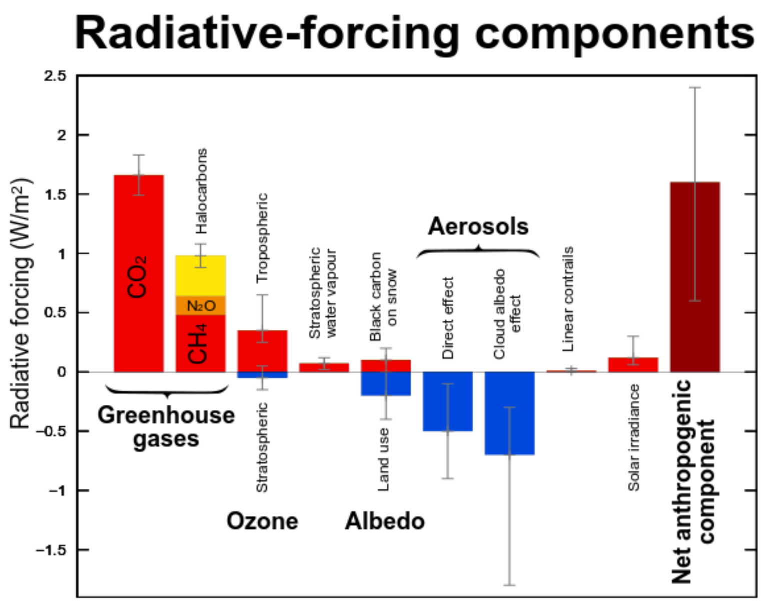
Cooling of the stratosphere







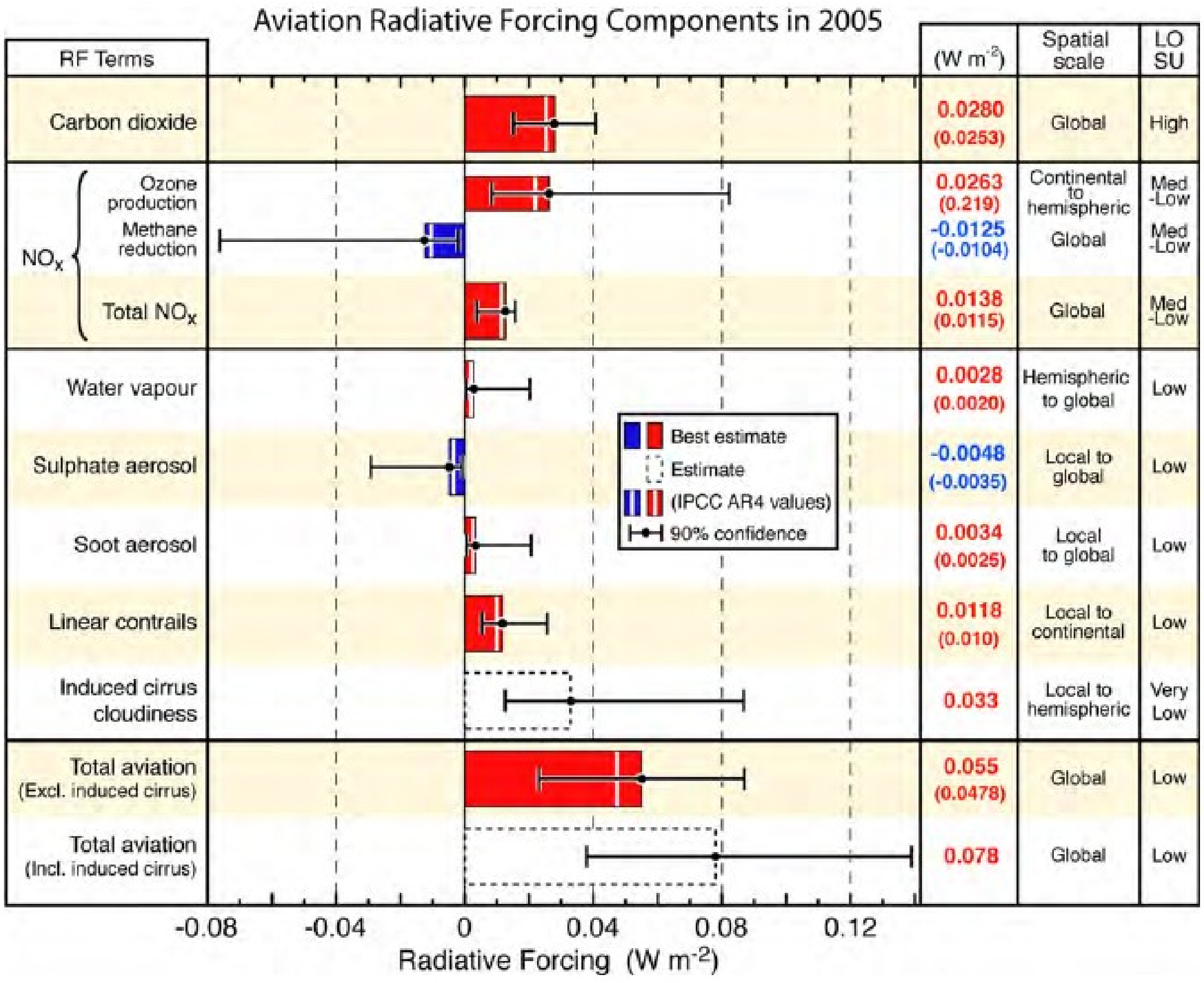
Estimating radiative forcing components (IPCC 2014) => **1.5 *W/m²***



« Fly me to the moon »

Radiative forcing for planes => a probable factor 2 with respect to mere combustion.

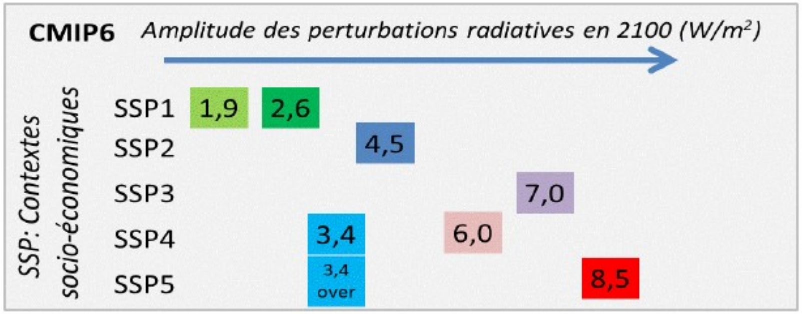
D.S. Lee et al. / Atmospheric Environment 44 (2010) 4678–4734



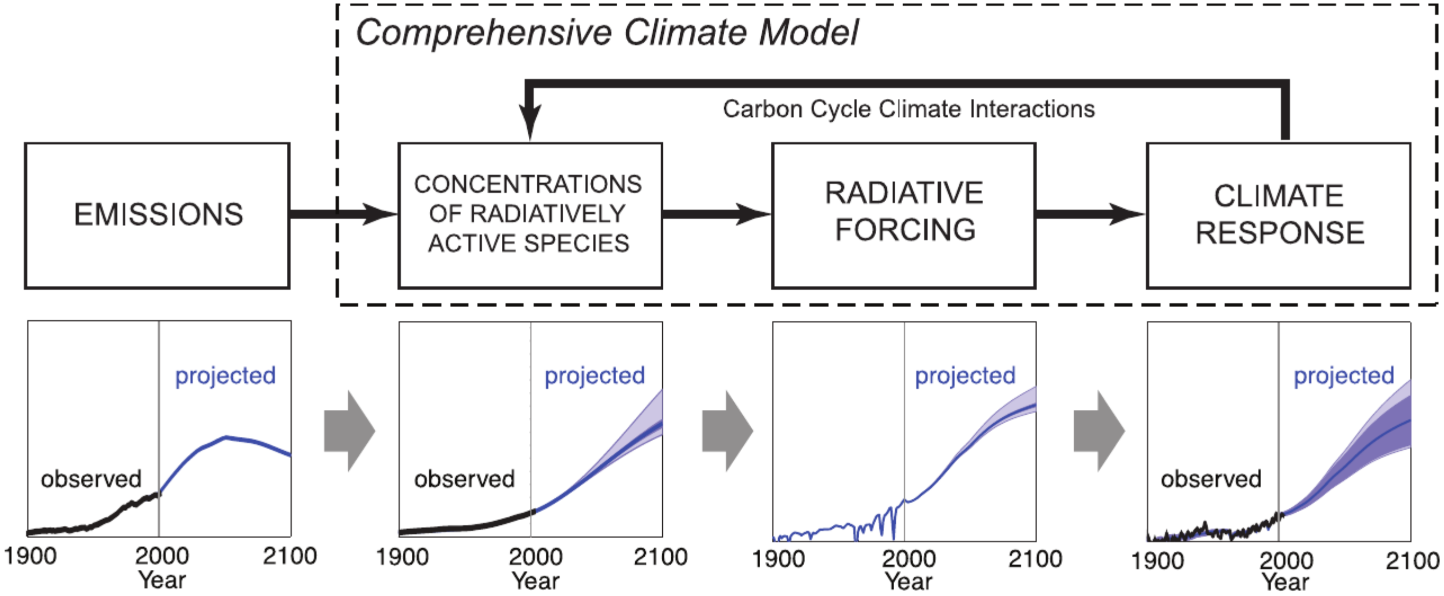
Predictions modelling (sept 2019)

- Nomenclatura

  requires socio-economical modeling of future emissions

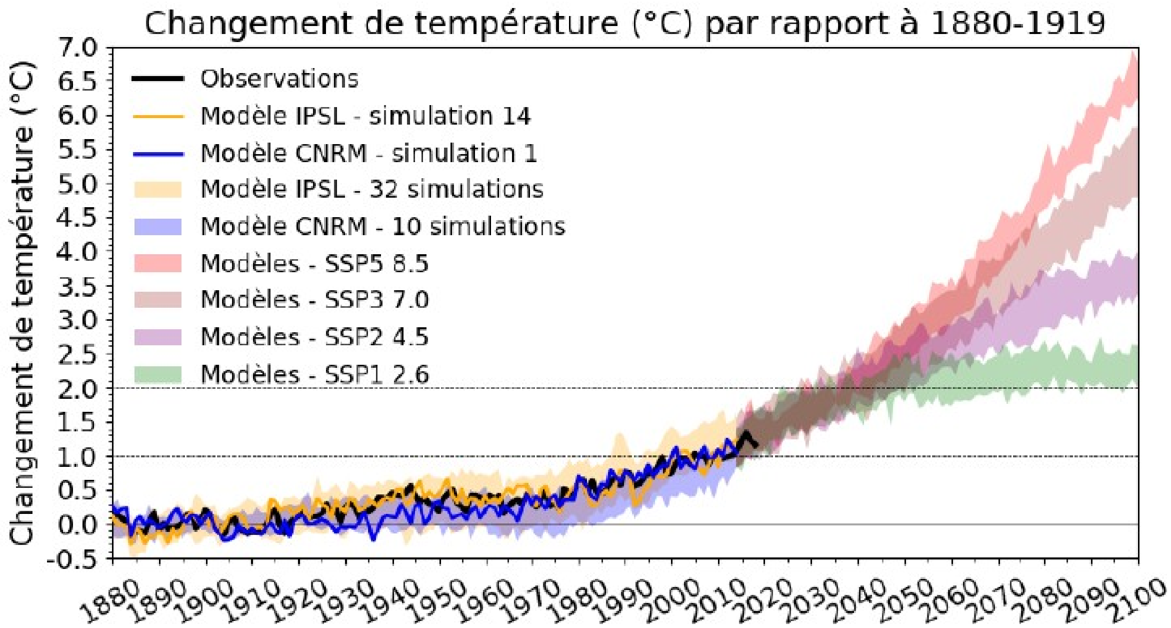


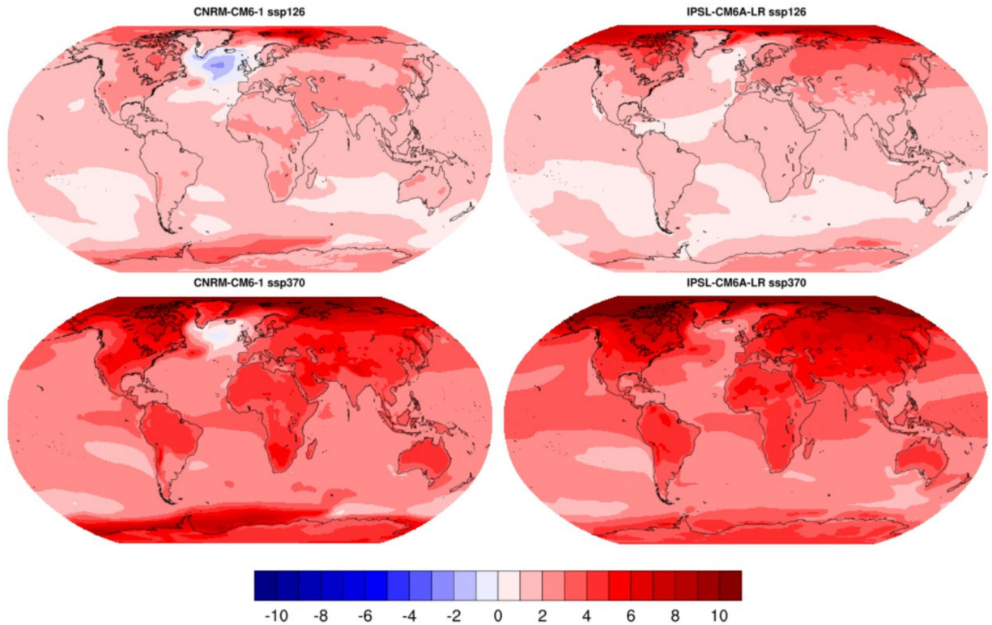
- Principle



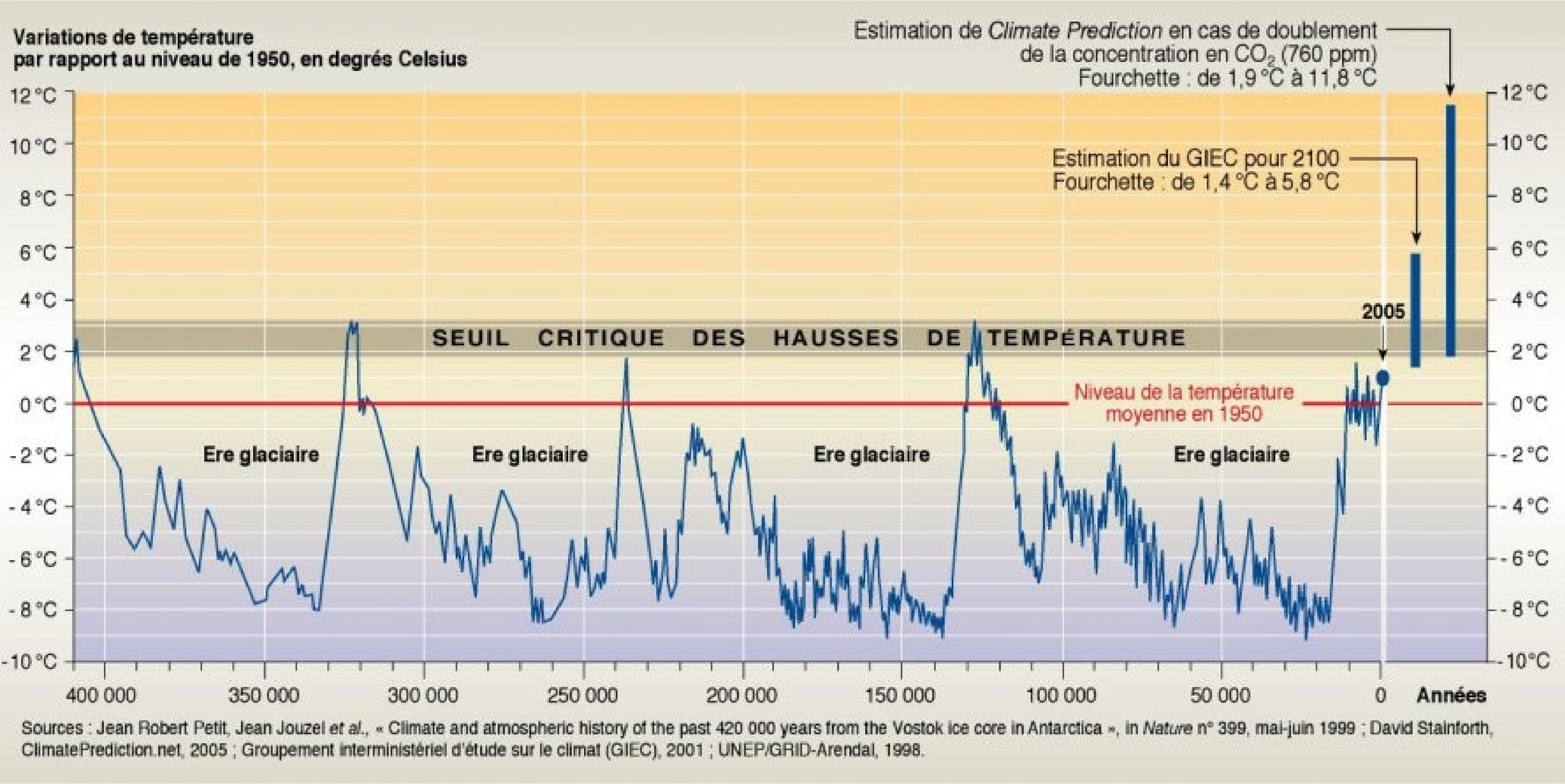
Scenari and predictions (sept 2019)

- Results





Road to unknown temperatures...



Probes of global warming and impacts

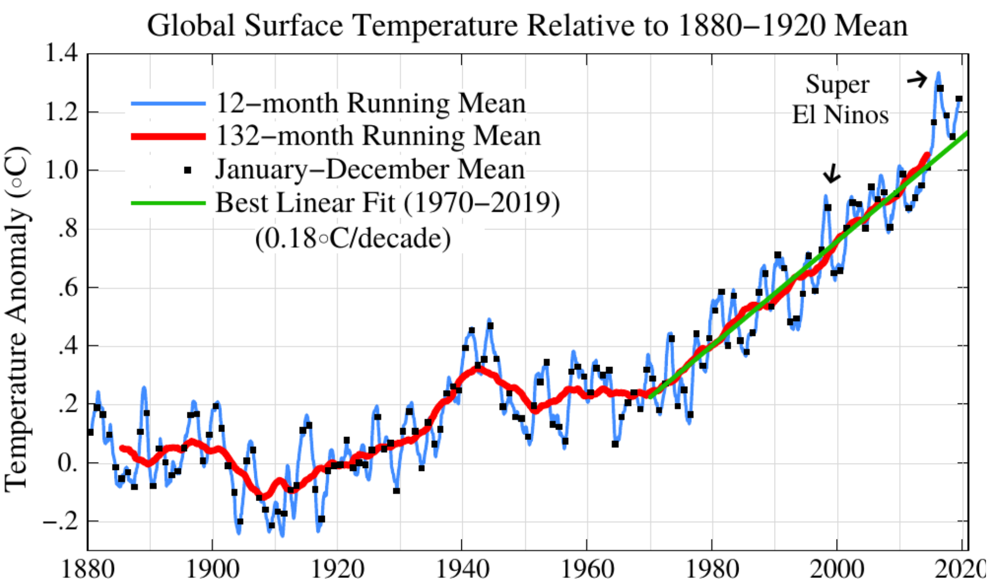
Global temperature anomaly trend

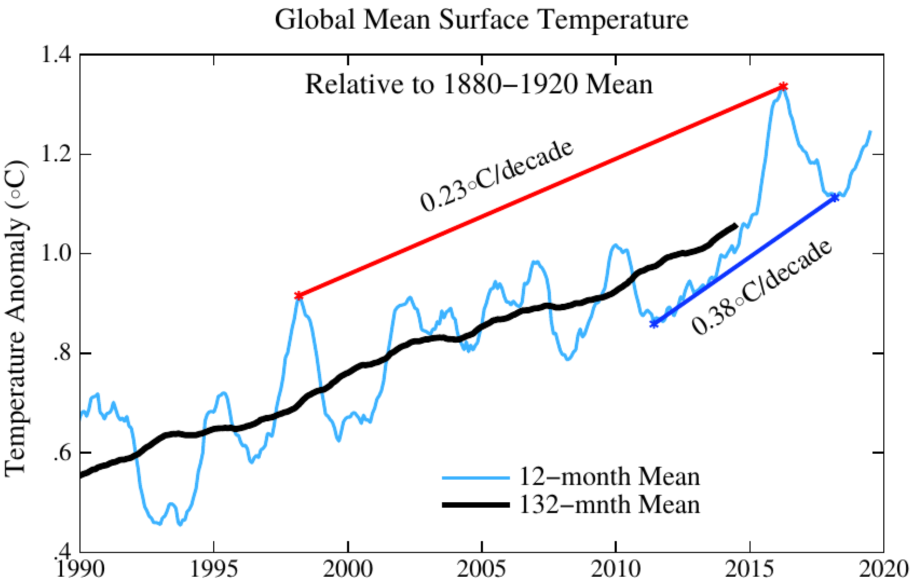
Data from Sato & Hansen http://www.columbia.edu/~mhs119/Temperature/

Last 50 years trend : 0.18°C/decade => 1.7°C (2050) and 2.6°C (2100)

Last 20 years trend : 0.23°C/decade => 1.9°C (2050) and 3.0°C (2100)

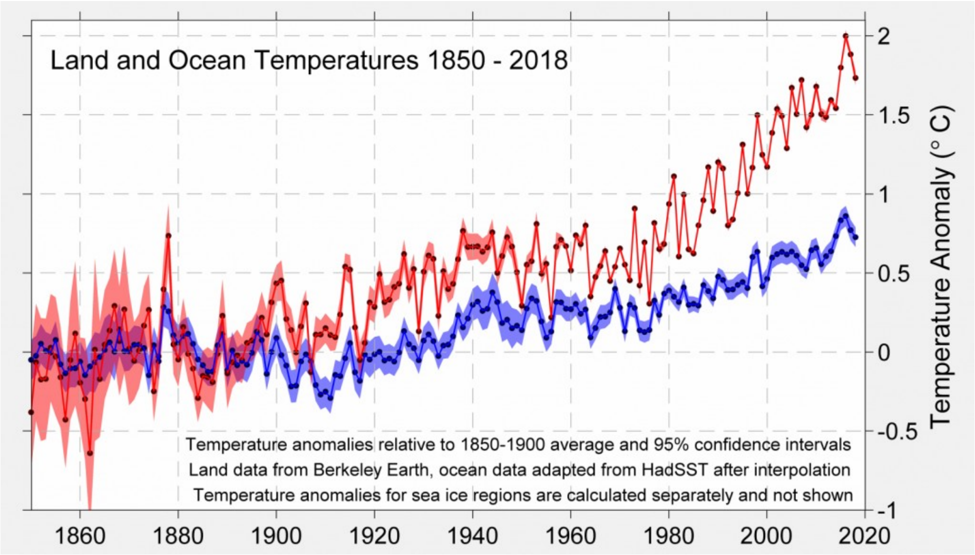
Last 8 years trend : 0.38°C/decade => 2.3°C (2050) and 4.2°C (2100)



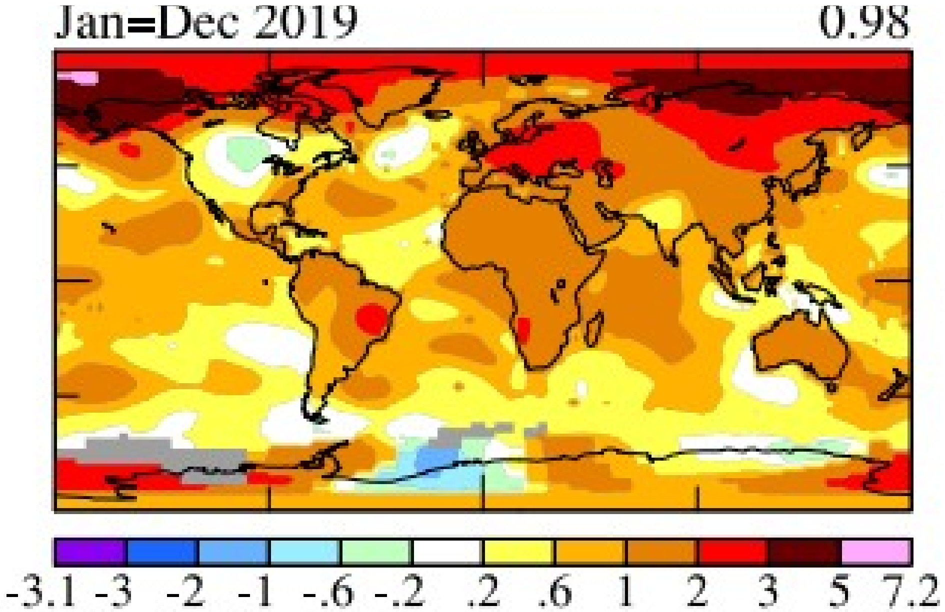


Spatial variations of global warming

Land vs ocean

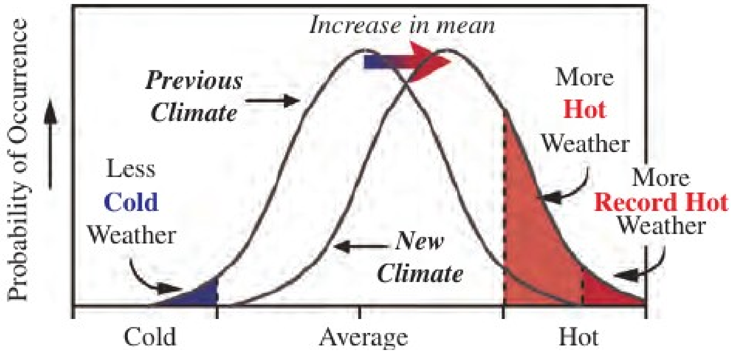


Lattitude dependence from Sato & Hansen http://www.columbia.edu/~mhs119/Temperature/



Shifting the average and rare events

Temperature distribution



Shifting the average and rare events

Temperature distribution

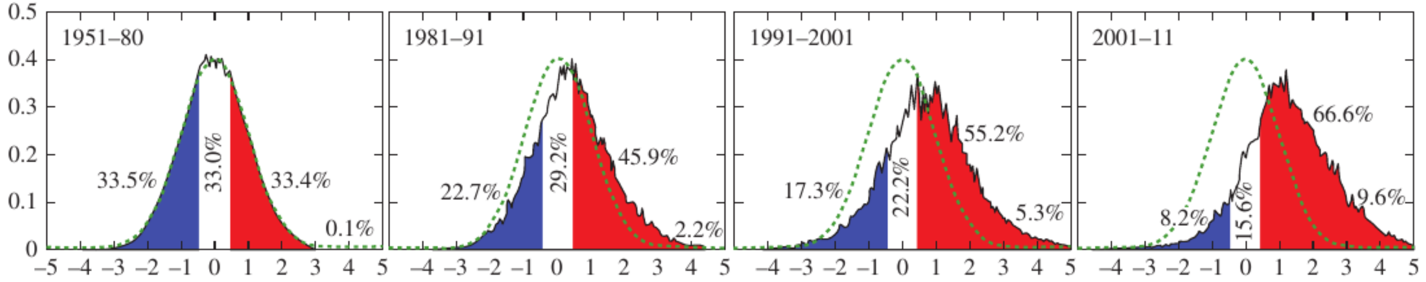


Fig. 25.9 The change in the frequency of local land June-August temperature anomalies (with respect to the 1951–80 mean) in the Northern Hemisphere in the past six decades (Hansen et al. 2012; Hansen et al. 2013a). The horizontal axis is in units of local standard deviation, σ.

Shifting the average and rare events

Temperature distribution

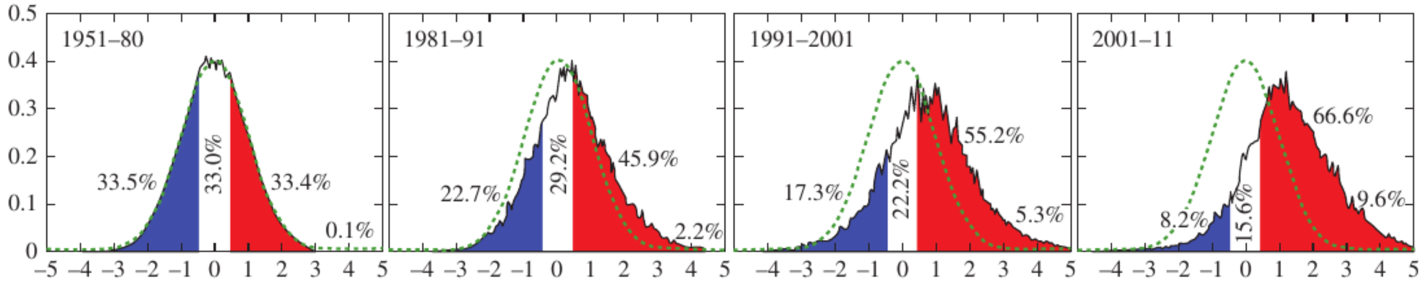
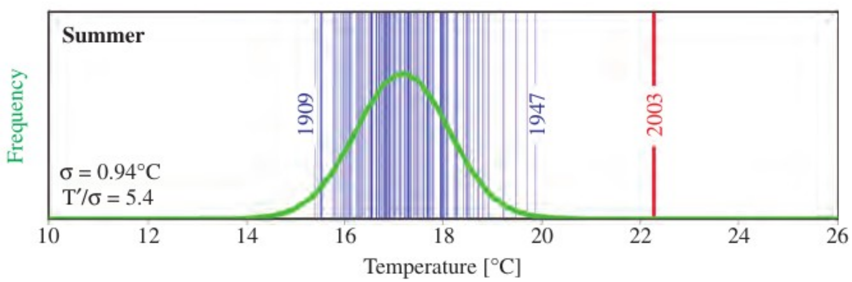
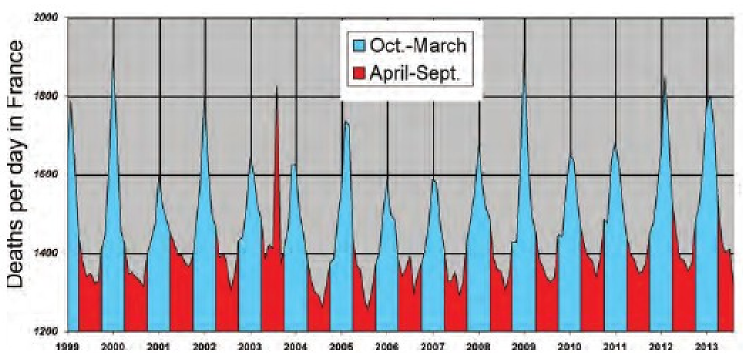


Fig. 25.9 The change in the frequency of local land June-August temperature anomalies (with respect to the 1951–80 mean) in the Northern Hemisphere in the past six decades (Hansen et al. 2012; Hansen et al. 2013a). The horizontal axis is in units of local standard deviation, σ.

2003 Canicule
=> expected to be the
standard summer conditions in 2100





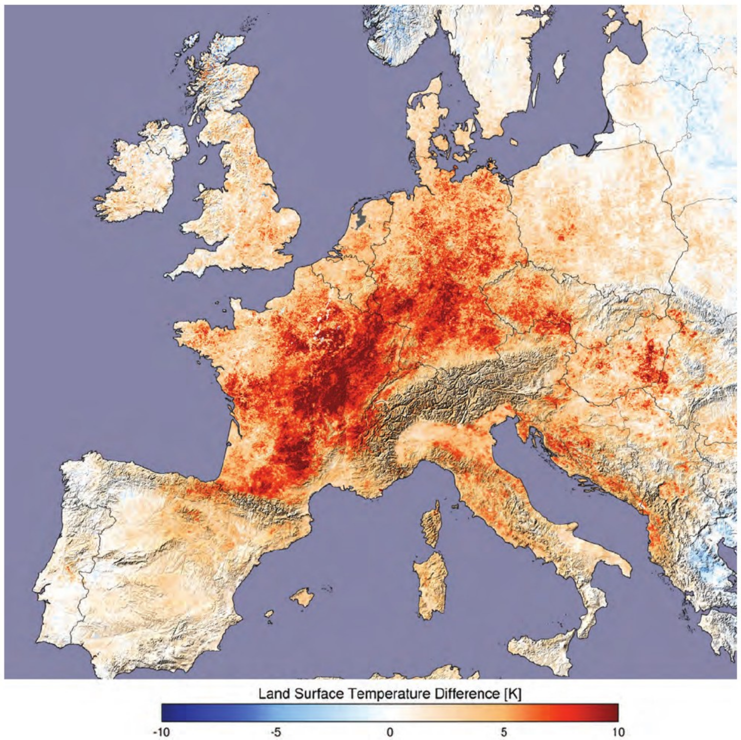
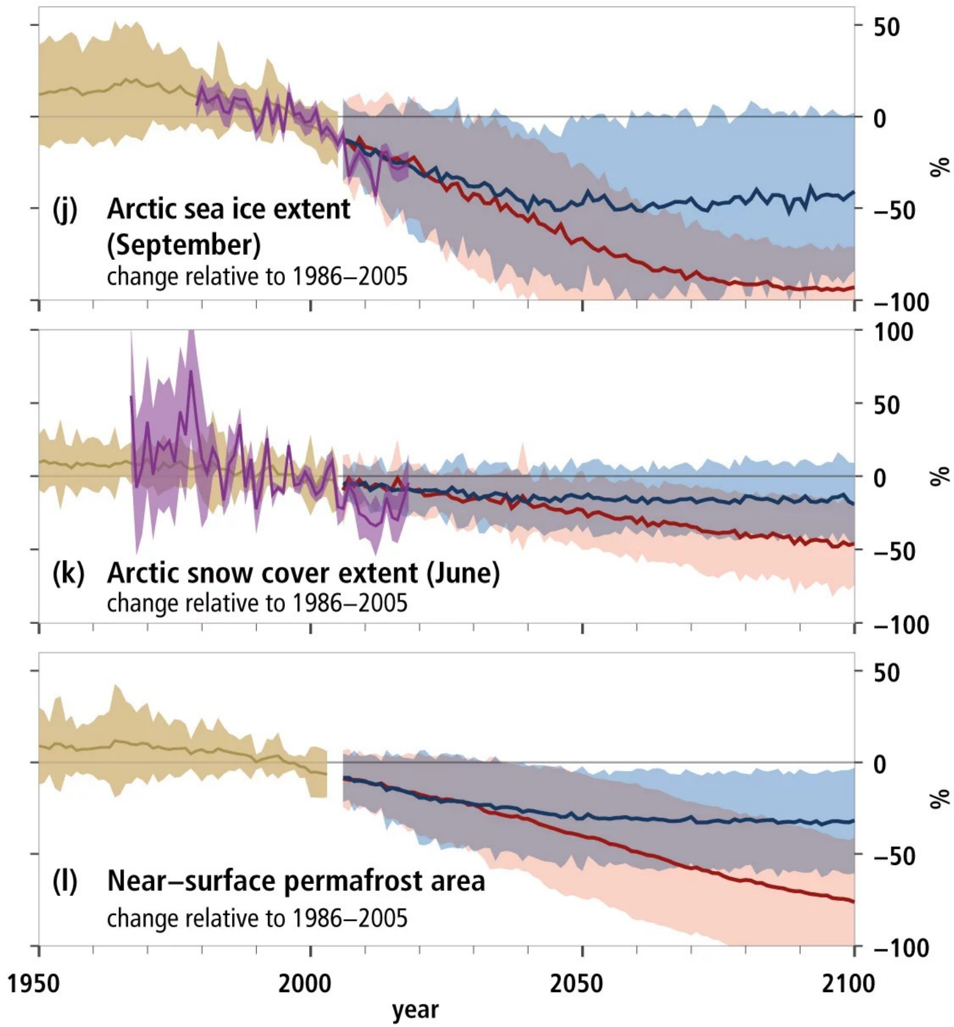


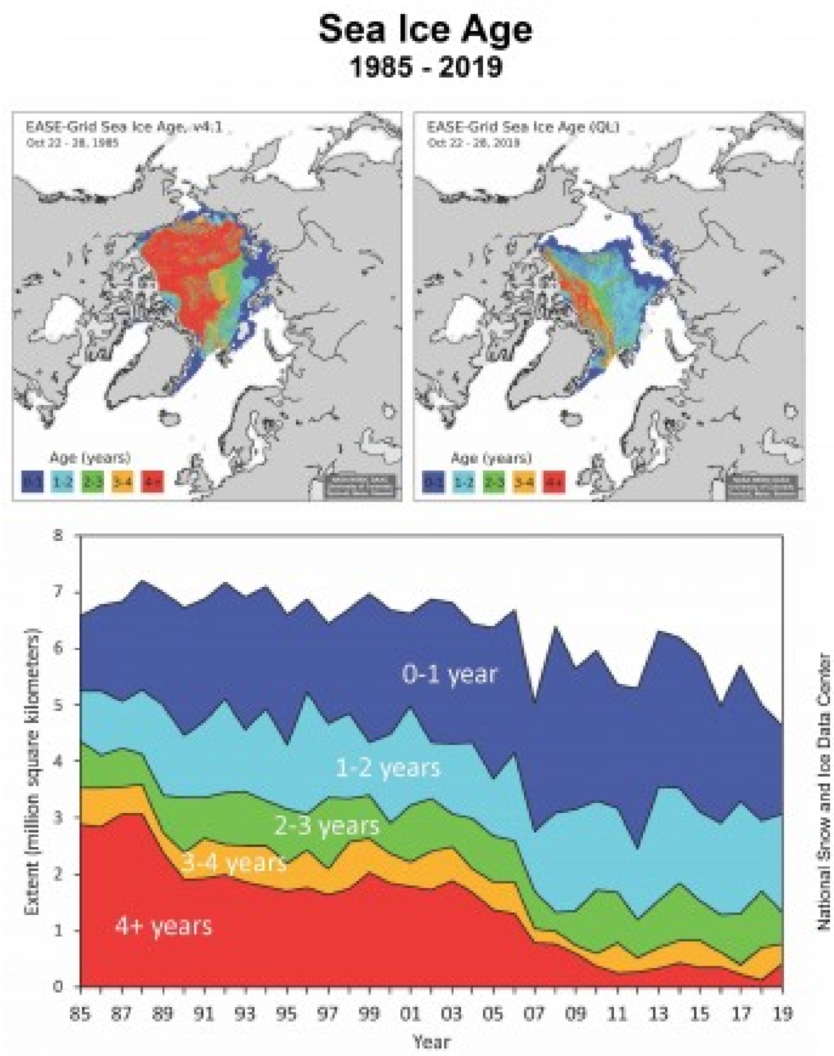
Fig. 25.6 The surface temperature anomaly over Western Europe in summer 2003, during the period 20 July to 20 August. The anomaly is calculated by subtracting from the 2003 measurements the average of observations made during cloudless days in 2000, 2001, 2002 and 2004.

Source: Reproduced with permission of Reto Stöckli.

Directs impacts : ice melting

Temperature threshold T~ 0°C

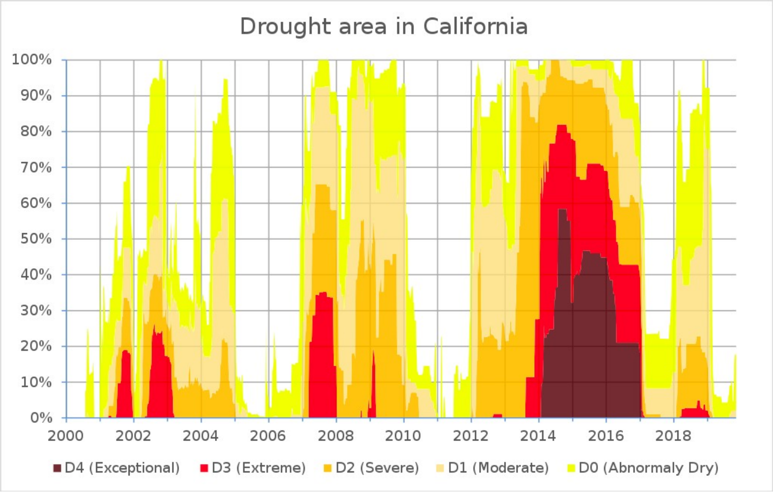




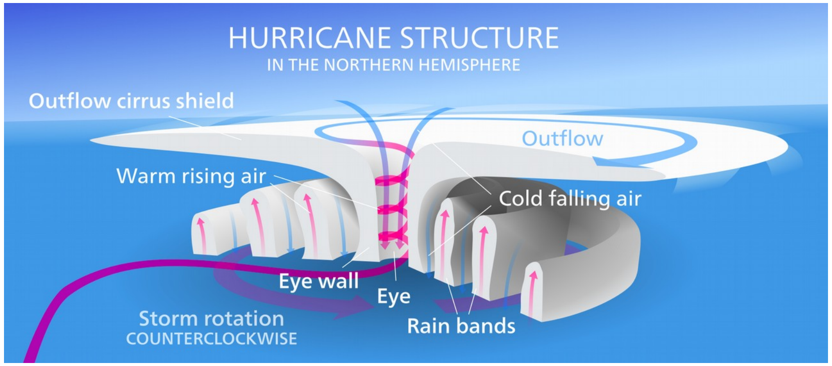
Directs impacts : hot limit

Mammals with hot blood : T~ 37°C => suffer from heat, in particular humid heat

Plants : at high temperatures (>40°C) photosynthesis decays, evaporation rate puts a huge stress on physiology

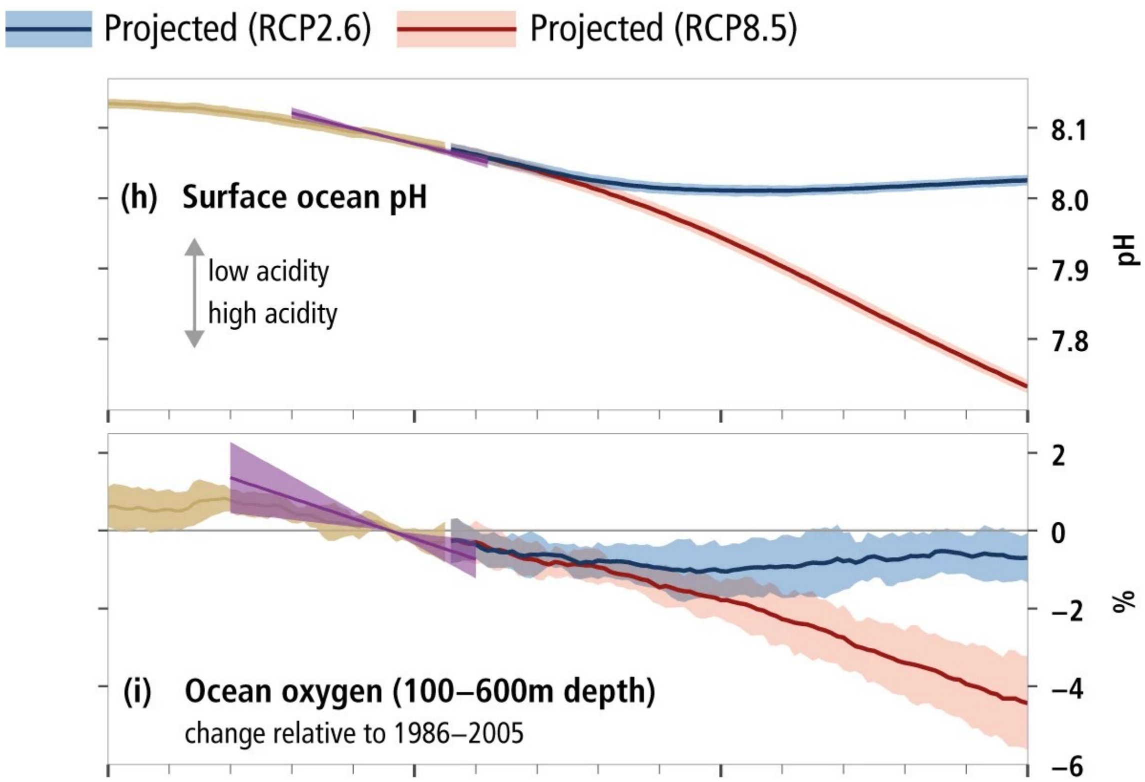


Hurricanes : requires water temperature of 26.5 °C down to 50m to develop.



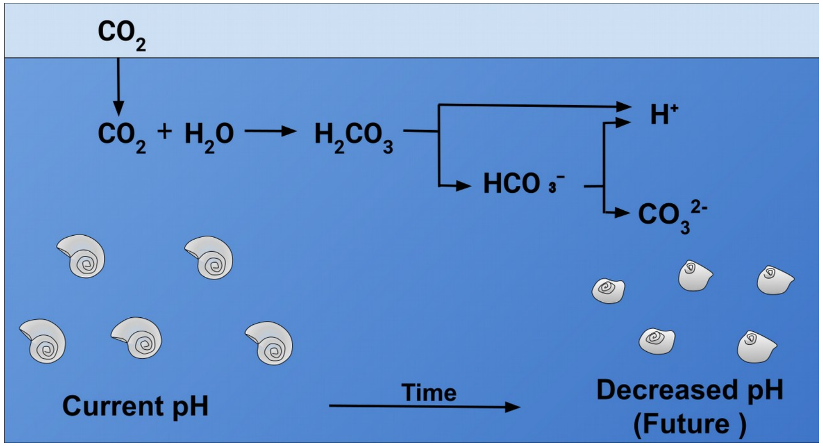
Floodings requires huge evaporation rates driven by hot temperatures

Directs impacts : ocean acidification

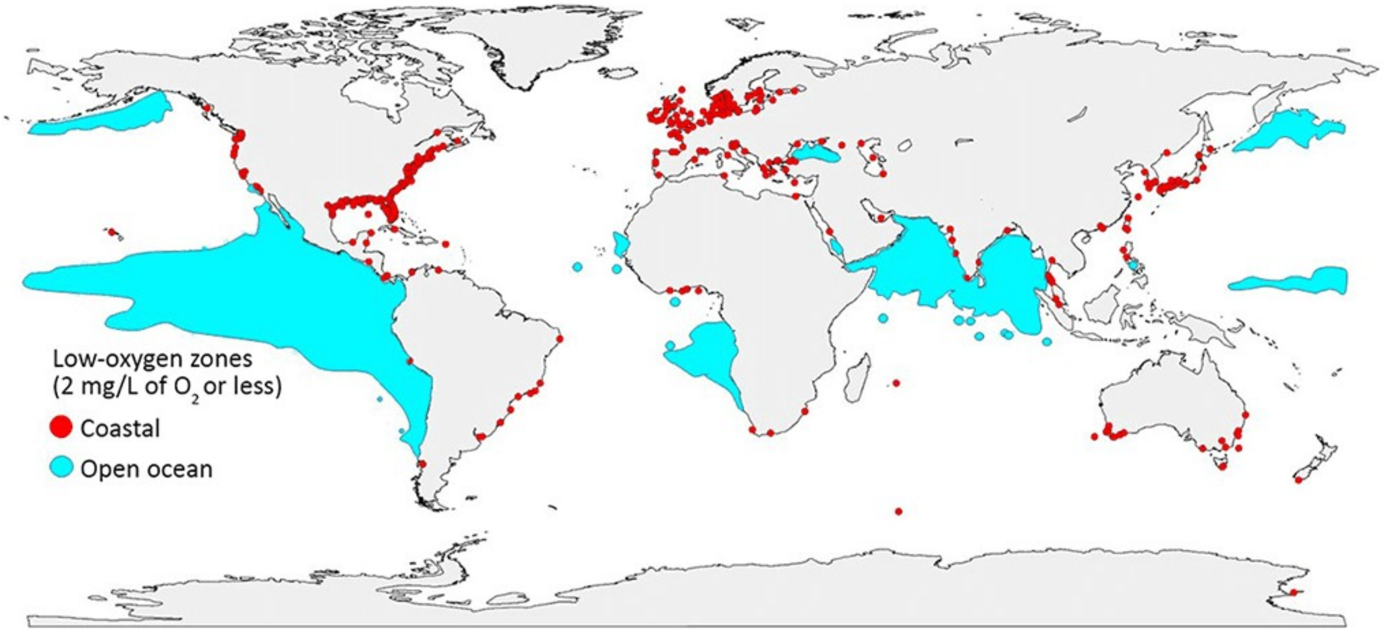


Directs impacts : ocean acidification

Many shells, corals, crabes skeleton are sensitive to pH



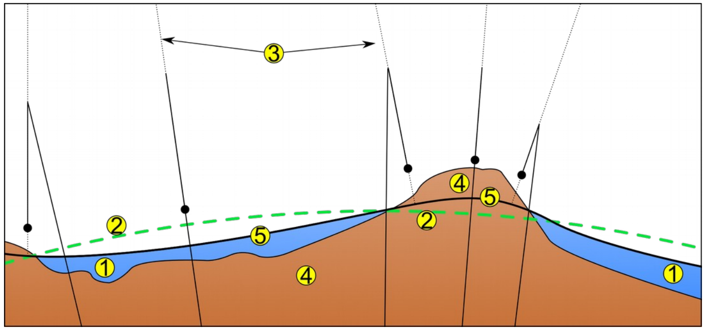
Decrease of oxygen => dead zones

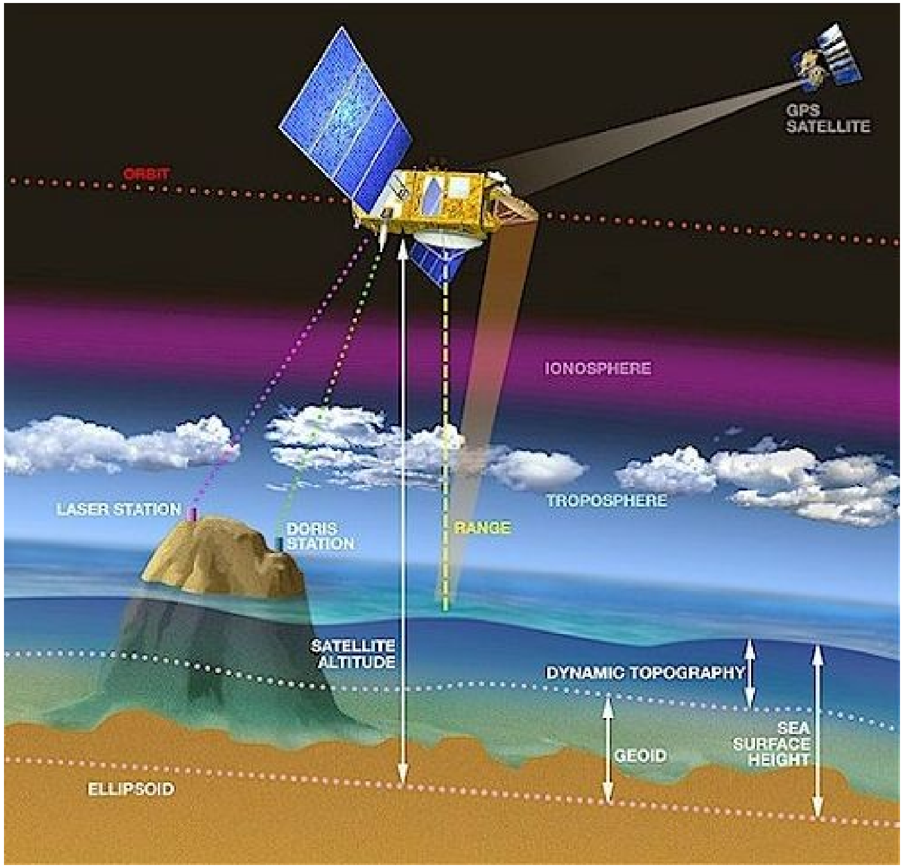


Measuring the sea level

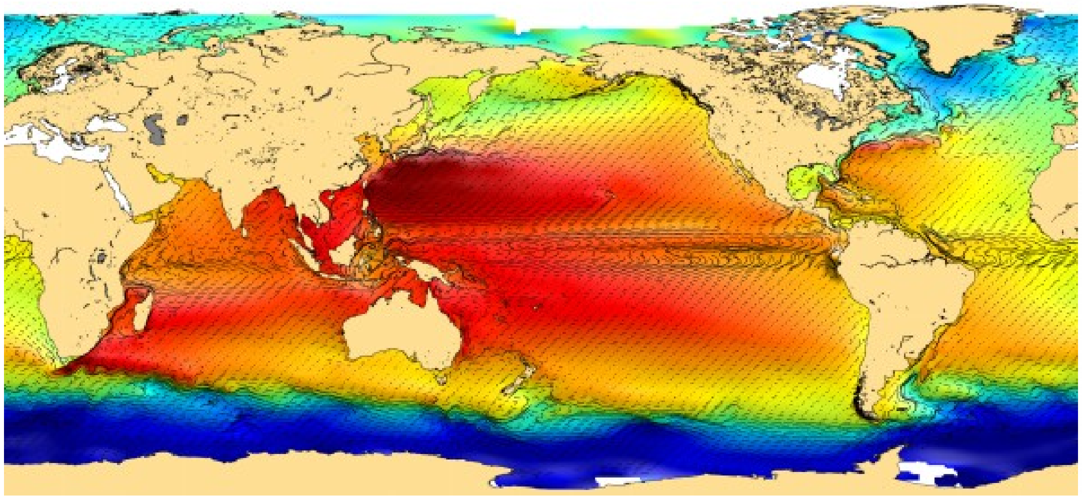
- Dynamical topography with satellites (Topex Poseidon 1992 and before)
- Measure echo of radar pulses reflected from the surface of the ocean
- Satellite orbit is located using ground stations (Doris)

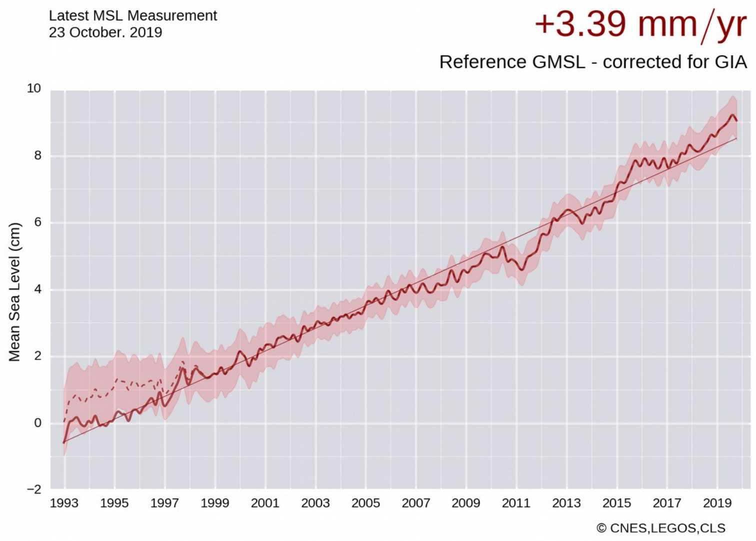
- The see level reference is taken with respect to the geoid : an gravity equipotential line such that the vertical is locally perpendicular to it (known with precision by gravimetry)





Measuring the sea level

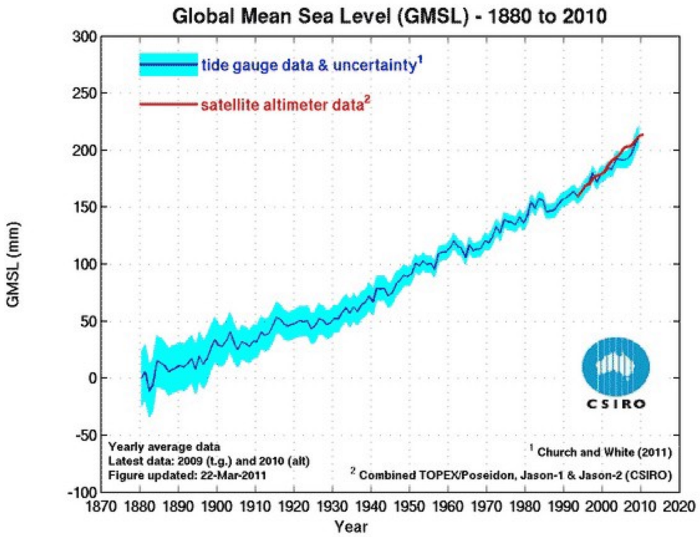




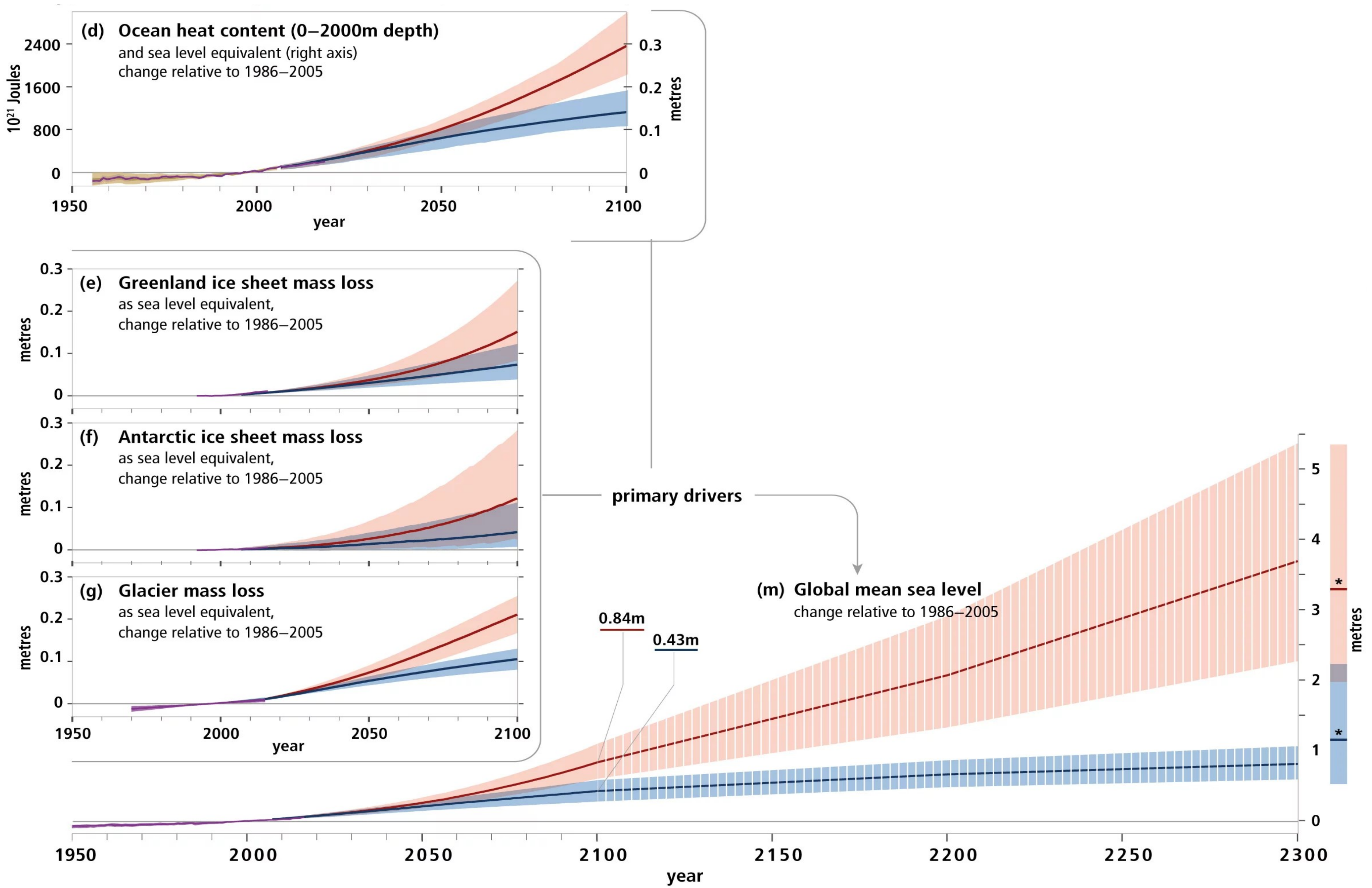
- Other techniques:

  Maregraph (scale, pressure,...)

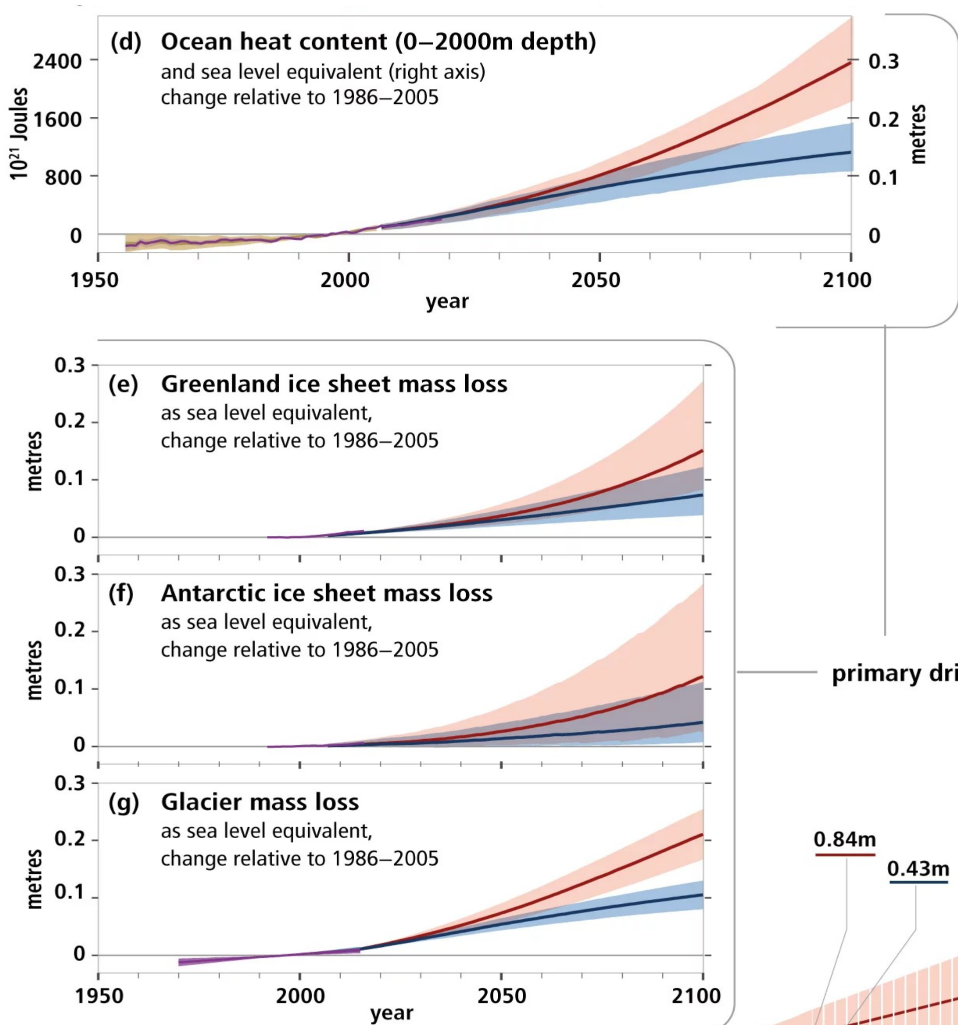
  Gravimetry by observing the deviation from Kepler in satellites orbits
  => estimate of volume / mass of ocean (how much ice has melted)

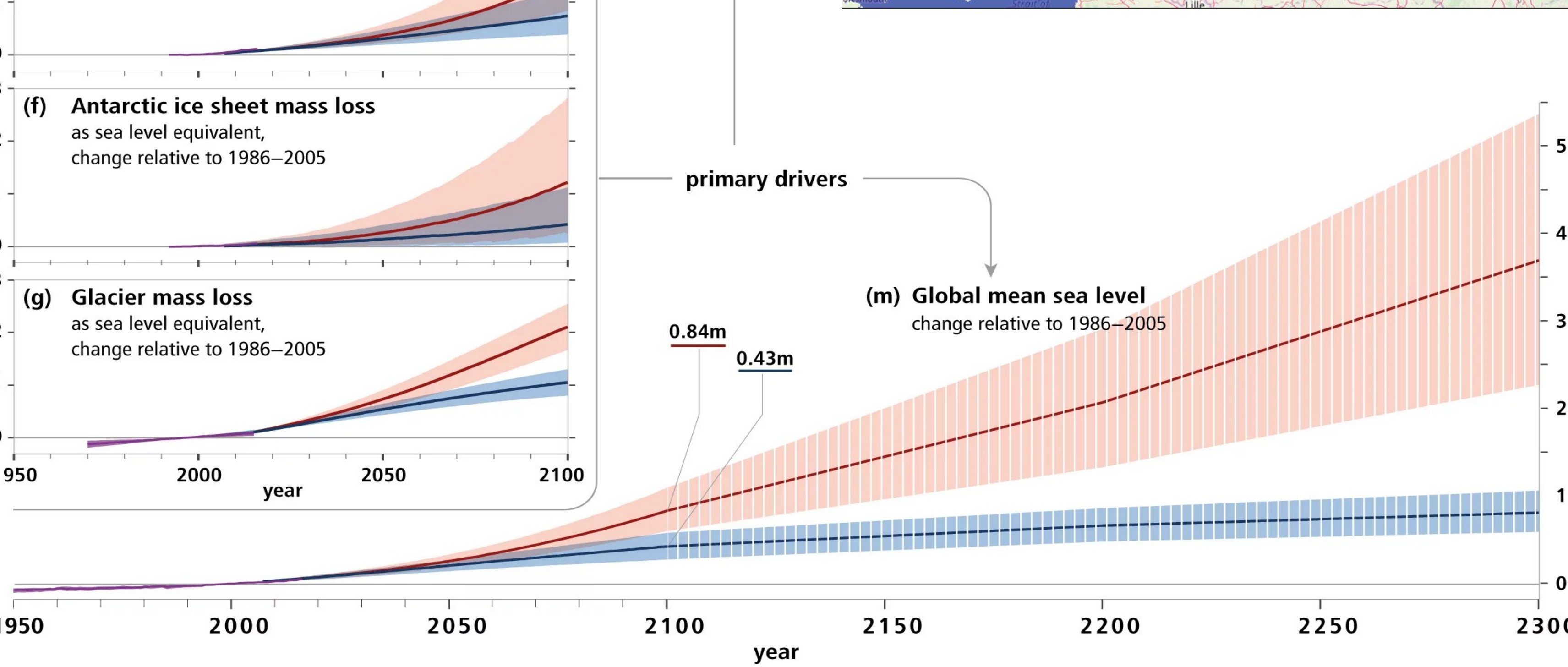


Elevation of ocean levels (IPCC 2019)



Elevation of ocean levels (IPCC 2019)





Questions and project ideas ?

-
-
-
-

Questions and project ideas ?

- Climates of the past, human / climate interaction
- The carbon cycle
- Refined models of greenhouse effect
- Circulations and fluid simulations
- Measurements and data analysis
- The IPCC prediction modelling