

The consequences of an increase of the atmospheric CO₂ concentration, a global survey of our current state of knowledge

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Abstract: The present rapid increase of the atmospheric CO₂ and other greenhouse gases concentrations due to human activities could induce very serious modifications of the Earth's environmental conditions. This paper intends to summarize our present knowledge about the two main consequences of such unprecedented – as far as the rate of change is concerned – modification of our atmosphere composition, i.e. the global warming effect and the decrease of the ocean pH (ocean acidification). A particular emphasis is placed on the demonstration that there are clear and indisputable scientific evidences of a CO₂ interaction with the infrared radiations reemitted through the atmosphere by the Earth's surface leading to an increase of the so-called “greenhouse effect”, in spite of the opposite assertions of a few “climate skeptics”.

Keywords: Carbon dioxide, Global warming, Greenhouse gas, Infrared energy, Ocean acidification.

1. Introduction

From the beginning of historical times, human activities have influenced in a noticeable way the environment on Earth. Agriculture, deforestation, or irrigation are examples of human actions which induced in the past, and are still inducing a lot of pressure on nature. With the present level of industrial development, as well as the exponential increase in world population, this pressure has become so large that it has led to a rate of change of our environment never observed before. This could have consequences without any common measure with anything already seen in the past. Today, human beings consume every second over 155'000 liters of oil, approximately 90'000 cubic meters of gas and more than 200'000 kg of coal [2]. In the last two hundred years, this fossil energy consumption caused an increase in atmospheric CO₂ concentrations from 280 ppm in the middle of the 19th Century to 388 ppm in 2010. Moreover, the average rate of greenhouse gas (GHG) atmospheric concentration increase measured between 1995 and 2005 was 1.9 ppm per year, which is considerable compared to the 0.0002 ppm of the annual average rate of increase recorded in the previous 650'000 years [1]. Today, our carbon dioxide emissions significantly influence our environment and alter some natural balances. The future evolution of these GHG releases will depend on technological, political, economic and demographic factors. Technological solutions are being investigated and proposed by engineers; these include, among others, improved energy efficiency measures and technologies as well as the future

implementation of suitable carbon separation and sequestration techniques. Besides, a sustained educational effort toward populations on climate and energy issues needs to be made, and in this also engineers have an important part to play.

This paper intends to present a review of the most relevant elements of the current state of the scientific knowledge concerning the two main consequences of an increase of the CO₂ atmospheric concentration, which are:

- 1) the modification of the radiative energy balance in the atmosphere that is causing the global warming effect.
- 2) the modification of the hydrogen potential (pH) of the ocean, which could threaten the entire food chain,

The information presented here is a synthesis of knowledge published in scientific journals.

2. The role of CO₂ in global warming

The following facts regarding the climate evolution are hardly disputable:

- Over the last 100 years (1906-2005), the average temperature at the Earth's surface rose by 0.74 ° C [1].
- The concentration of atmospheric carbon dioxide (CO₂) rose from 280 ppm (pre-industrial value) to 388 ppm (value in 2010), whereas this concentration had increased by only 20 ppm in the previous 8000 years [1].
- Carbon dioxide is a gas that interacts with the infrared electromagnetic energy emitted from the Earth's surface through the atmosphere [15].

On the other hand, the explanations of the causes of the observed climate change over the last hundred years are subject to controversies. The major role played by the atmospheric CO₂ increase in the greenhouse effect is assessed in many reports published by the IPCC (Intergovernmental Panel on Climate Change) [1]. But the IPCC conclusions are challenged by a small group of scientists, the often called "climate skeptics". These scientists dispute the fact that atmospheric CO₂ may participate in global warming. They question the importance attributed to the greenhouse effect described in the reports published by the IPCC.

What are the lessons to be learned from paleoclimatology studies ?

Paleoclimatology studies highlight the fact that during interglacial periods of significant warming, high levels of atmospheric CO₂ concentration played an essential role through greenhouse effect. Major publications in this area [9, 10, 11, 12, 13, 14] suggest:

- 1) the existence of a clear correlation between the astronomical Milankovitch¹ cycles and the transitions between glacial and interglacial periods on Earth,
- 2) a difference in behavior between the northern hemisphere and southern hemisphere during periods of warming,
- 3) the fact that ice and CO₂ play a decisive role in the appearance of interglacial warming periods.

In a recent paper, G.H. Denton [14] explains the development of the penultimate interglacial period. He highlights that an interglacial period cannot start only because of increased solar irradiation resulting from the Milankovitch cycles. It is necessary to also have a debacle characterized by the melting of the ice cap in the North Atlantic (figure 1); such ice collapse causes a disruption of all the ocean currents with an upwelling of deep waters in the southern hemisphere. This upwelling releases large quantities of CO₂ into the atmosphere, resulting in turn in a strong surface warming due to the greenhouse effect induced by this CO₂. The authors of

¹ Milankovitch Theory describes the collective effects of changes in the Earth's movements upon its climate. Milanković mathematically theorised that variations in eccentricity, axial tilt, and precession of the Earth's orbit determined climatic patterns on Earth. Source : Wikipedia

this paper [14] highlights that, during glaciation periods, sunlight can increase without inducing a reversal of climate trends. **This is a clear proof that the CO₂, and not the Sun, is responsible for the global warming observed during interglacial periods [14].**

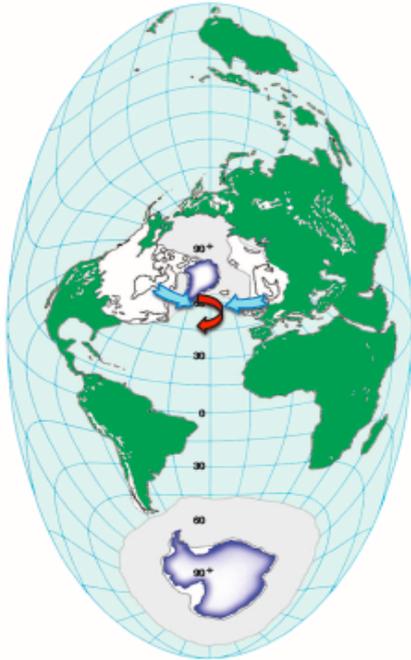


Figure 1 : Illustration of the ice collapse in the northern hemisphere [14]

What do we know about the greenhouse effect ?

Greenhouse gases (GHG) are molecules (H₂O, CO₂, CH₄, O₃, CFCs,...) that interact with infrared (IR) electromagnetic radiations. They absorb parts of the IR radiation spectrum emitted by the Earth's surface, and then transfer this energy to the surrounding molecules. This absorption can be measured in the laboratory.

Figure 2 shows the absorption spectrum of CO₂ molecules, measured by Jacques Gentili at the Material Science Laboratory of the "École Normale Supérieure" of Lyon (France) [15]. These measures display CO₂ energy absorption lines at wavelengths of 4.3 μm and 15 μm.

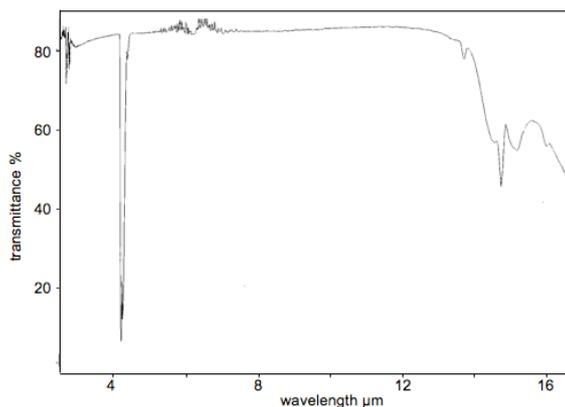


Figure 2 : Absorption spectrum of the IR radiation by the CO₂ molecule [15]

The interactions between the infrared energy emitted by the Earth's surface and the atmosphere are obviously extremely complex since they imply interactions between photons and molecules. These interactions of radiation and matter depend on the thermodynamic equilibrium.

Infrared photons propagating through the atmosphere interact with the various GHG molecules they encounter. These molecules absorb these photons and then become themselves energy emitters. In the lower atmosphere, where Local Thermodynamic Equilibrium (LTE) exists, this absorbed energy is essentially transferred by momentum exchange resulting from the collisions with the molecules, mainly O_2 or N_2 , surrounding the GHG molecules. Considering the density of the lower atmosphere, it takes more time for the CO_2 molecule to emit an IR photon than to interact with the nearby molecules. In the higher atmosphere, where the density is low and thus no LTE exists, the IR photons emission dominates; the IR photons absorbed by the various GHG molecules are reemitted in all directions, including downwards. It is however also possible that the GHG molecules in the higher atmosphere absorb energy by momentum exchange and only then release infrared photons.

To sum up, part of the flux of infrared energy emitted by the Earth's surface is intercepted by the GHG molecules and then transformed mainly into internal energy (thermal agitation) in the lower atmosphere, but reemitted in all directions under the form of IR photons in the higher atmosphere. All this physical process constitutes the greenhouse effect. The net balance of these interactions however remains a flux of infrared energy lost into space. This flux is composed of the IR photons that are not intercepted by the atmosphere and those that are emitted upwards by the low density zones present in the upper layers of the atmosphere [16]. This energy flux towards space is lower than the one emitted by the Earth's surface.

The climate skeptics claim that these interactions between IR photons and greenhouse gas molecules are negligible in the energy balance of the Earth. Evidence that such is not the case is that it is possible to measure this absorption of IR photons by greenhouse gas at various heights from space via satellites. Measuring this infrared flux absorption is precisely the main objective of the Greenhouse gases Observing SATellite (GOSAT) project, see [19].

What about major atmospheric convection currents?

In equatorial and tropical zones, the Earth receives more energy per unit area than in the polar regions. Major oceanic and atmospheric convection currents carry part of the inter-tropical energy in the direction of the poles. As far as the atmosphere is concerned, these major convective currents are organized in the form of more or less active cells (Hadley cell, Ferrel cell, polar cell, Walker cell). The question is to know whether the magnitude of this convective energy exchange is as important as that of the radiative energy linked to the greenhouse effect. Information on this subject can for example be found in the documents [1] and [4].

The diagram below gives an order of magnitude of these various vertical energy fluxes.

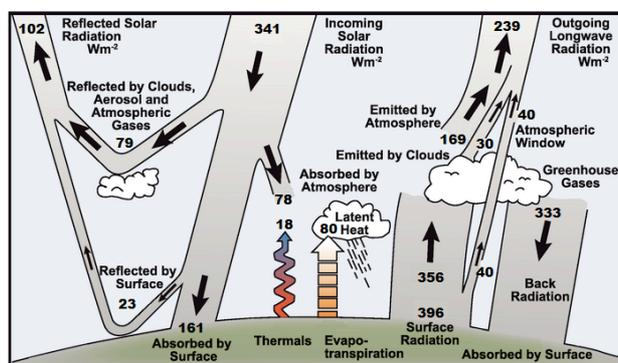


Figure 3: Illustration of the vertical energy fluxes from the sun, the surface and in the atmosphere ; values based on [4], with slight adjustments to get a net balance of the atmospheric energy fluxes equal to zero.

As can be seen in figure 3, the infrared fluxes, downwards and upwards, due to the various greenhouse gases present in the Earth's atmosphere globally exceed 500 W/m^2 , whereas the convective flows, including the one due to the latent heat of water, barely reach 100 W/m^2 .

There is a big difference between these two types of streams. Infrared fluxes are present at all times and everywhere in the atmosphere. On the other hand, convective flows only exist in given areas and they are intermittent. In general the atmosphere is stable, in other words is layered, and the dominating movements are horizontal. Large vertical displacements exist only in specific locations and under specific conditions. They are clearly visible in figure 4 in the form of "white packs" in the equatorial region. Elsewhere, ascent and subsidence zones are created as a result of the presence of high and low pressures. It is therefore not surprising that infrared fluxes are in average much larger than the convective flows.

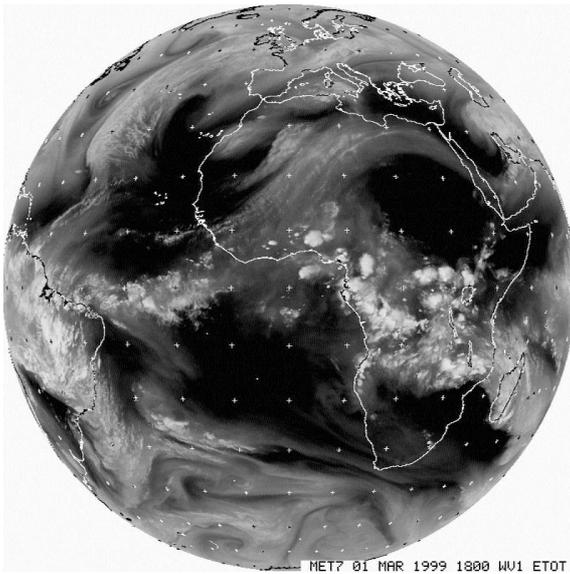


Figure 4 : Meteosat picture [15]

Thus, to pretend that the radiative fluxes due to the atmospheric CO_2 play no role in the current warming is not backed up by any serious scientific analysis [16].

What can be observed from space?

For more than 50 years, Earth has been observed by satellites, but observation satellites dedicated to the measurements of the atmospheric CO_2 levels started in 2004 only, with the setup of the Greenhouse gases Observing SATellite (GOSAT) project [20]. GOSAT is a joint project of MOE (US Ministry of the Environment), JAXA (Japan Aerospace Exploration Agency) and NIES (US National Institute for Environmental Studies). Currently, the most up-to-date technique for obtaining global maps of CO_2 concentration from spaceborne platforms is based on the detection of the energy absorption of CO_2 , exploiting passive measurements in the Near InfraRed (NIR) - $1,6\mu\text{m}$ et $2\mu\text{m}$ - and Thermal InfraRed (TIR) - $4,3\mu\text{m}$ et $15\mu\text{m}$ - regions [18].

Launched on January 23, 2009, the Japanese satellite IBUKI has since then provided measurements allowing the precise monitoring of the density of CO_2 . These data are presently being studied, but it is still too early to draw definitive conclusions.

OCO (Orbiting Carbon Observatory) is an American satellite that is designed to measure the fraction of CO_2 in the atmosphere. After the failure of the launch of the satellite OCO-1 on February 24th, 2009, NASA decided

to prepare a new OCO - 2 mission, the launch of which is planned for February 2013. This satellite will join a satellite constellation (figure 5), called the A-Train [21].

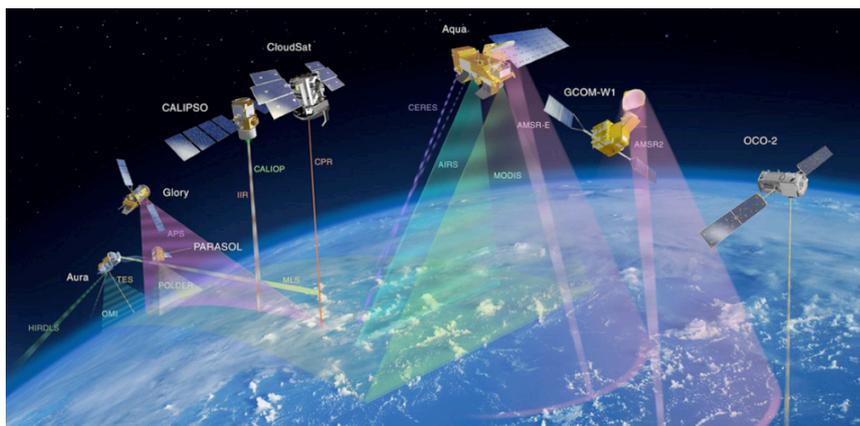


Figure 5 : A-Train satellite constellation, illustration from NASA [21]

These two examples (IBUKI and OCO) show not only that great efforts are being made to monitor the atmospheric CO₂ concentration levels, but also that the CO₂ infrared absorption is a measurable reality.

Unfortunately, the satellite Glory, presented on figure 5, failed to reach orbit on March 4, 2011. It would have greatly increased our understanding of the Earth's energy balance (<http://glory.gsfc.nasa.gov>).

3. The role of CO₂ in ocean acidification

The hydrogen potential (pH) is a measure of the acidity of a medium. A pH above 7 indicates a basic medium, a pH below 7 means that the medium is acidic; the lower the pH value, the higher the acidity. The current decrease of the ocean pH is observed by all scientists who study the marine environment. Their studies clearly show that this decrease in pH is due to the increase of the atmospheric CO₂ concentration. The average pH of surface water is currently about 8.05 (figure 6). It has decreased by 0.1 since the beginning of the industrial era and this decline is 100 times faster than any change that the marine organisms had to withstand for at least 20 million years [3].

This increase in acidity due to human activities continues at such a rate that the oceans could become corrosive to the aragonite present in the shells of certain marine organisms before the end of the 21st century [3].

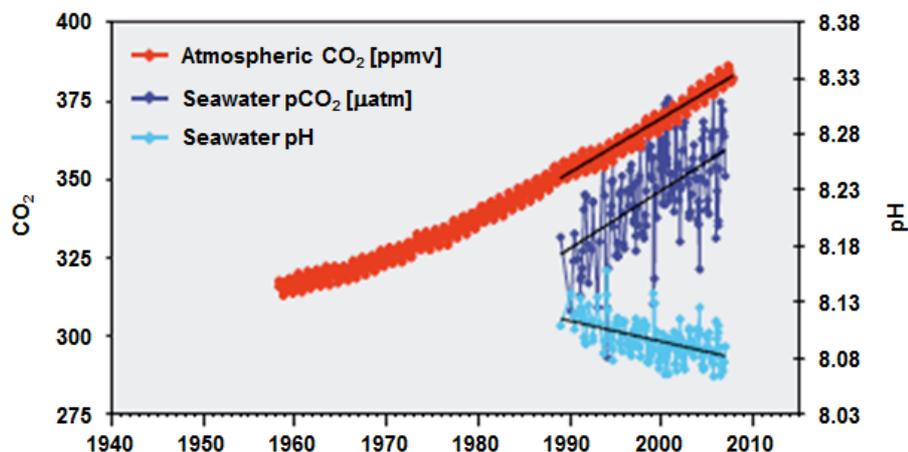


Figure 6 : CO₂ and pH time evolutions in the North Pacific Ocean [3]

It is important to specify that this change of pH is directly results from our CO₂ emissions, not an indirect consequence of global warming. Indeed CO₂ dissolves in water, where it chemically reacts according to the following main reactions [8] :

1. Formation of carbonic acid with subsequent release of hydrogen ions (reversible reaction)

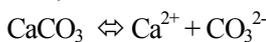


The dissociation of carbon dioxide thus increases the concentration of H⁺ ions and therefore decreases the pH of the water. This decrease of pH could eventually cause a metabolic acidosis on senior marine organisms [6].

2. Reaction with CO₃²⁻ ions already present in the water (reversible reaction)



This reaction decreases the concentration of CO₃²⁻ ions. This decrease of carbonate ions alters the balance between solid calcium carbonate (CaCO₃), or limestone, and CO₃²⁻ and Ca²⁺ ions in solution in water (reversible reaction) :



The equilibrium condition entails that the product of the concentrations of Ca²⁺ ions and CO₃²⁻ ions remains constant. In other words, if the concentration of carbonate ions decreases, the equilibrium condition is not satisfied any more. This leads to the dissolution of solid limestone present in water. This dissolution increases the concentration of calcium ions and carbonate ions in such a way that the product of both can remain constant and the equilibrium condition is again satisfied.

The dissolved limestone can come from two different crystalline forms: calcite and aragonite; shells and marine mollusks exoskeletons are constructed from either of these two solid forms, or a combination of both. With a concentration of CO₃²⁻ below 66 micromoles per kg, water is no more saturated in aragonite and the latter becomes soluble in water (figure 7). Below this limit, the production of aragonite by living organisms decreases. Micro-mollusks like pteropods (whose shell is cone-shaped, figure 8), that are a vital link in the food chain at high latitudes, are particularly threatened by such chemical modifications of water [5].

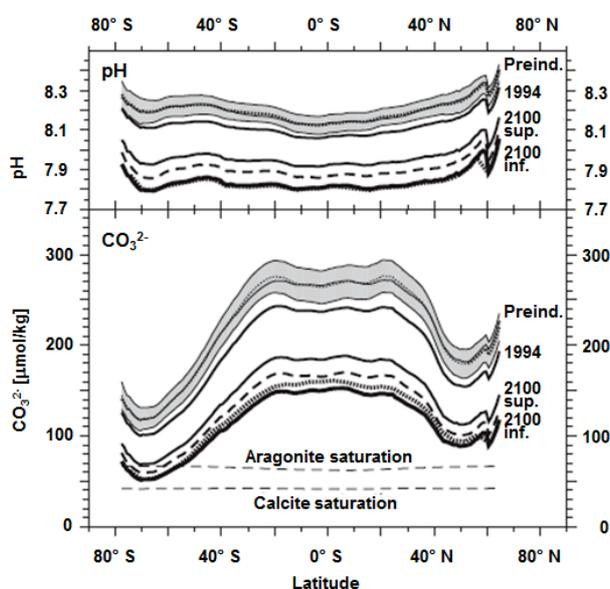


Figure 7 : decreasing surface ocean pH and [CO₃²⁻] [5]

According to James C. Orr [5], the surface water of the ocean at high latitudes may reach this limit of 66 micromoles per kg by the end of the 21st century and thus cause the disappearance of the pteropods (figure 8). This could have dramatic consequences for all animals that feed on these microorganisms (some species of zooplankton, salmon, herring, mackerel, whales, etc.).



Figure 8 : *Pteropod arctic Limacina helicina* (Spitzberg), © S. Comeau, LOV [22]

Fifty-five million years ago, at the end of the Paleocene (during the so-called "Paleocene - Eocene thermal maximum"), there was an episode of sharp increase in the acidity of water, of the concentration of atmospheric CO₂, and of the average temperature. The pH decrease occurred very quickly, i.e. in a few hundreds of years only; the oceans required then approximately one hundred of thousand years to come back to the previous situation, resulting in a major extinction of living species [8].

The acidification rate today is 10 times faster. The Ocean Acidification Reference User Group [8] notes in this regard that: "Today, atmospheric CO₂ levels are increasing considerably faster than the ocean water can mix, forcing these processes out of alignment. The result is that most CO₂ is building up in a layer of sea water near the ocean surface. About 50% of all the CO₂ we have emitted resides in the upper 10% of the ocean. The ability of sediments to regulate ocean chemistry and neutralize the acidity is simply too slow – taking place over more than 1000 years – and so ocean pH and the amount of available carbonate ions are now declining".

4. Conclusion

Current knowledge clearly demonstrates that the increase in atmospheric CO₂ concentration is the main cause of global warming through the greenhouse effect and the increase of the acidity of the oceans. The rate of this increase is such that it could lead to changes in our environment at a rate and scale never known before [1, 8, 17]; this is illustrated in figure 9.

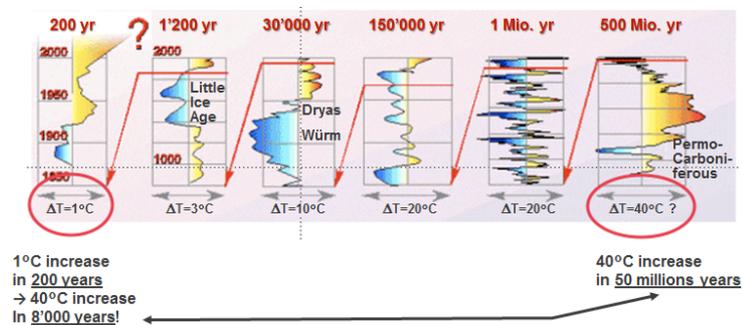


Figure 9 : Illustration of the present acceleration of the rate of Earth's surface temperature increase compared to the changes that happened in the past, adapted from [23]

Although such a rapid temperature change represents a potential risk unprecedented in human history, the international community seems to still have the greatest difficulty in mobilizing to fight anthropogenic CO₂ emissions. Energy, economic, demographic, and political issues often make consider as a second priority the necessity to reduce our consumption of fossil fuels and/or find ways to sequester the emitted CO₂ at the source. The economic development of disadvantaged populations, as well as the global increase in World population, hinder the control of the rapid increase in CO₂ emissions. Improving energy efficiency is one of the key factors that can contribute to the reduction of these emissions. Engineers have a fundamental role to play in this field by their contribution to improving the acceptance of these new technologies by a large public. To this end, engineers must actively participate in the effort to inform the citizens not only on climate and energy issues but also on the concrete technological options available to solve these problems.

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- Fig 4 Image Meteosat, source [15]
- Fig 5 A-Train, illustration credit NASA, source :
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