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Thermo-Hydraulic Drivers of the Global Climate System

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Abstract: A lot of effort is required from the humanity to preserve the global climate from changes that could make the living conditions on Earth unsustainable. Decarbonization of the energy sector is meant to give the key contribution by humans to keep the global temperature rise by the end of this century below levels determined by the Paris Agreement. Transition from fossil to renewable and other energy sources that do not emit greenhouse gases is an inevitable goal for the humanity to preserve natural cabon cycle from a risky inbalance. As the climate system on Earth is extremely complex, there is no possibility for climate change phenomena to be examined in a laboratory like the majority of the thermo-hydaulic phenomena is, the thermal engineers and scientists are left to depend only on historic records and mathematical simulations of an extremely large quantity of climate change drivers studied within several tens or hundreds of scientific disciplines. Still, many of the inter-relations or feedbacks among climate phenomena remain quite uncertain or entirely unknown, so that many of the climate change drivers need to be identified and explaned to make humanity aware of all the risks to be prevented in fighting against climate change beyond repair. The paper lists the major known thermo-hydraulic and other drivers of the climate system and related open questions in the field of the thermal science as a pathway for further research and studies of thermal and hydaulic kind in the climate system.

Keywords: climate change, thermal science, solar radiation feedbacks, climate models.

1. Introduction

The climate system is an interactive system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, forced or influenced by various external forcing mechanisms, the most important of which is the Sun. Many physical, chemical and biological interaction processes occur among the various components of the climate system on a wide range of space and time scales, making the climate system extremely complex. Any change, whether natural or anthropogenic, in the components of the climate system and their interactions, or in the external forcing, may result in climate variations. The following sections introduce various aspects of natural climate variations and the human influence on the climate system. Although the components of the climate system are very different in their composition, physical and chemical properties, structure and behaviour, they are all interrelated and linked by fluxes of mass, heat and momentum, the major laws of the thermal science. As the current climate science is mainly based on statistical averaging of hystorical and current data over space and time and mathematical presentations of the climate drivers, it is of utmost importance to better undestand nature and mechanisms of these drivers.

The *atmosphere* is the most unstable and rapidly changing part of the system and is composed mainly of nitrogen (N_2, 78.1%), oxygen (O_2, 20.9%, and argon (Ar, 0.93%), which have only limited interaction with the incoming solar radiation and they do not interact with the infrared radiation emitted by the Earth [1]. However, there also are a number of trace gases, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3), which do absorb and emit infrared radiation. These so called greenhouse gases, with less than 0.1% by volume, play an essential role in the Earth's energy budget, as does also the water vapour (H_2O), which is also a natural greenhouse gas, whose volume mixing ratio is highly variable (typically in the order of 1%). Because these greenhouse gases (GHGs) absorb the infrared radiation emitted by the Earth and emit infrared radiation up- and downward, they tend to raise the temperature near the Earth's surface. Beside these gases, the atmosphere also contains solid and liquid particles (aerosols) and clouds, which interact with the incoming and outgoing radiation in a complex and spatially very variable manner. The most variable component of the atmosphere is water in its various phases such as vapour, cloud droplets, and ice crystals. Water vapour is the strongest GHG and for these reasons and because the transition between the various phases absorb and release much energy, water vapour is central to the climate and its variability and change.

The *hydrosphere* is the component comprising all liquid surface and subterranean water, both fresh water, including rivers, lakes and aquifers, and saline water of the oceans and seas. Fresh water runoff from the land returning to the oceans in rivers influences the ocean's composition and circulation. The oceans cover approximately 70% of the Earth's surface and store and transport a large amount of energy as well as dissolve and store great quantities of CO_2. Their circulation, driven by the wind and by density contrasts caused by salinity and thermal gradients (the so-called thermohaline circulation), is much slower than the atmospheric circulation. Mainly due to the large thermal inertia of the oceans, they damp vast and strong temperature changes and function as a regulator of the Earth's climate and as a source of natural climate variability, in particular on the longer time-scales.

The *cryosphere*, including the ice sheets of Greenland and Antarctica, continental glaciers and snow fields, sea ice and permafrost, derives its importance to the climate system from its high reflectivity (albedo) for solar radiation, its low thermal conductivity, its large thermal inertia and, especially, its critical role in driving deep ocean water circulation. Because the ice sheets store a large amount of water, variations in their volume are a potential source of sea level variations.

Vegetation and soils at the *land surface* control how energy received from the Sun is returned to the atmosphere: some is returned as long-wave (infrared) radiation, heating the atmosphere as the land surface warms, and some serves to evaporate water, either in the soil or in the leaves of plants, bringing water back into the atmosphere. Because the evaporation of soil moisture requires energy, soil moisture has a strong influence on the surface temperature. The roughness of the land surface, determined by both topography and vegetation, influences the atmosphere dynamically as winds blow over the land's surface, [1].

The marine and terrestrial *biospheres* have a major impact on the atmosphere's composition. The biota influence the uptake and release of GHGs. Through the photosynthetic process, both marine and terrestrial plants (especially forests) store significant amounts of carbon from CO_2. Thus, the biosphere plays a central role in the carbon cycle, as well as in the budgets of many other gases, such as CH_4 and N_2O. Other biospheric emissions are the so-called volatile organic compounds (VOCs [1]) which may have important effects on atmospheric chemistry, on aerosol formation and therefore on climate.

Because the storage of carbon and the exchange of trace gases are influenced by climate, feedbacks between climate change and atmospheric concentrations of trace gases can occur. The atmosphere and the oceans are strongly coupled and exchange, among others, water vapour and heat through evaporation. This is part of the hydrological cycle and leads to condensation, cloud formation, precipitation and runoff, and supplies energy to weather systems. On the other hand, precipitation has an influence on ocean salinity, its distribution and the thermohaline circulation. Atmosphere and oceans also exchange CO_2, maintaining a balance by dissolving it in cold polar water which sinks into the deep ocean and by outgassing in relatively warm upwelling water near the equator. These are just a few examples from a virtually inexhaustible list of complex interactions some of which are poorly known or perhaps even unknown.

With this in mind, it is still a lot of research in the field of thermal and hydraulics sciences to be done in order to reduce some of numerous scientific uncertainties that feed skepticism on human influence on climate change ([2]) and thus delay global actions to reduce its impact on the risks of climate change beyond repair. The text which follows is an overview of the present knowledge of physical climate processes and feedbacks, both natural and anthropogenic (man induced) with an aim to indicate those shortcomings in science that could attract interest of researchers in the field of thermal and hydraulic sciences.

2. Drivers of the Climate Variation

2.1. Solar Radiation is the Main Driver of the Climate System

The ultimate source of energy that drives the climate system on Earth is radiation from the Sun. Each square metre of the Earth's spherical surface outside the atmosphere receives an average throughout the year of 342 Watts of solar radiation, ~ 30% of which is immediately reflected back into space by clouds, by the atmosphere, and by the Earth's surface, while the remaining 235 W/m^2 is partly absorbed by the atmosphere but most (168 W/m^2) warms the Earth's surface (the land and the ocean) [3]. The Earth's surface returns that heat to the atmosphere, partly as infrared radiation, partly as sensible heat and as water vapour which releases its heat when it condenses higher up in the atmosphere. This exchange of energy between surface and atmosphere maintains under present conditions a global mean temperature near the surface of 14°C, decreasing rapidly with height and reaching a mean temperature of –58°C at the top of the troposphere [4]. For a stable climate, a balance is required between incoming solar radiation and the outgoing radiation emitted by the climate system. Therefore the climate system itself must radiate on average 235 W/m^2 back into space. Shares of this energy balance can be seen in Figure 1, which shows on the left hand side what happens with the incoming solar radiation, and on the right hand side how the atmosphere emits the outgoing infrared radiation [3].

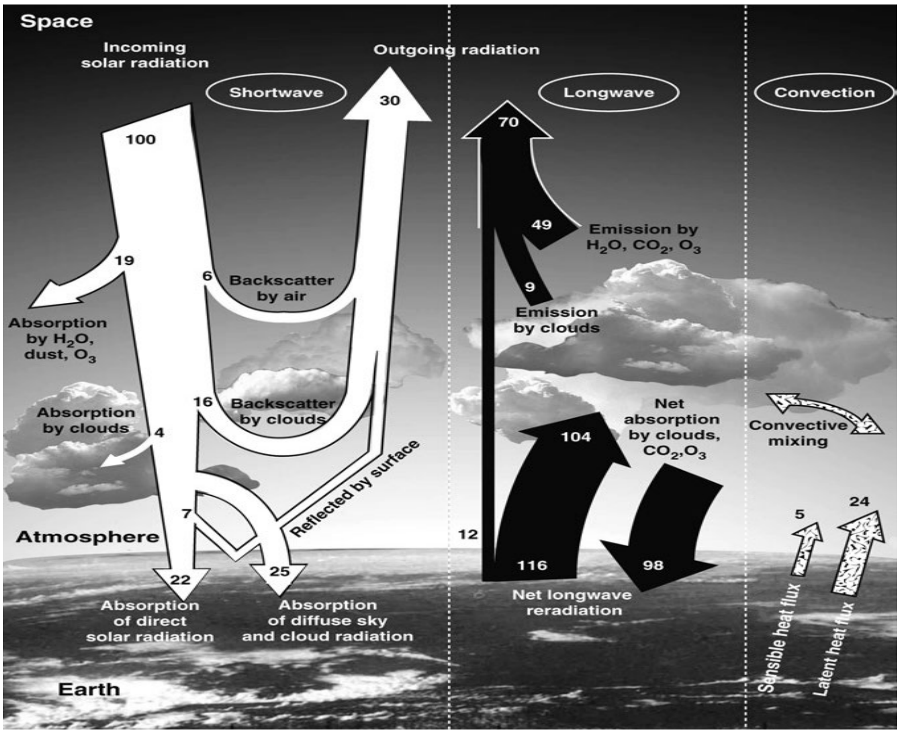


Figure 1: Shares of incoming and outgoing solar radiation

For the Earth to radiate 235 W/m^2, it should radiate at an effective emission temperature of −19°C which is 33°C lower than the average temperature of 14°C at the Earth's surface [4]. To understand why this is so, one must take into account the radiative properties of the atmosphere in the infrared part of the spectrum. Long-term records of atmospheric gases, obtained from atmospheric measurements and from air bubbles trapped in glacial ice, show large increases in the major radiatively active gases (CO_2, CH_4, N_2O, and chlorofluorocarbons - CFCs) since the beginning of the industrial revolution 250 years ago. Human activities such as fossil fuel burning, industrial activities, animal husbandry, and fertilized and irrigated agriculture contribute to these increases. As concentrations of these gases rise, the atmosphere traps more of the longwave radiation emitted by Earth, enhancing the greenhouse effect and increasing Earth's surface temperature as yearly averaged from 1850 shown on Figure 2 [5]

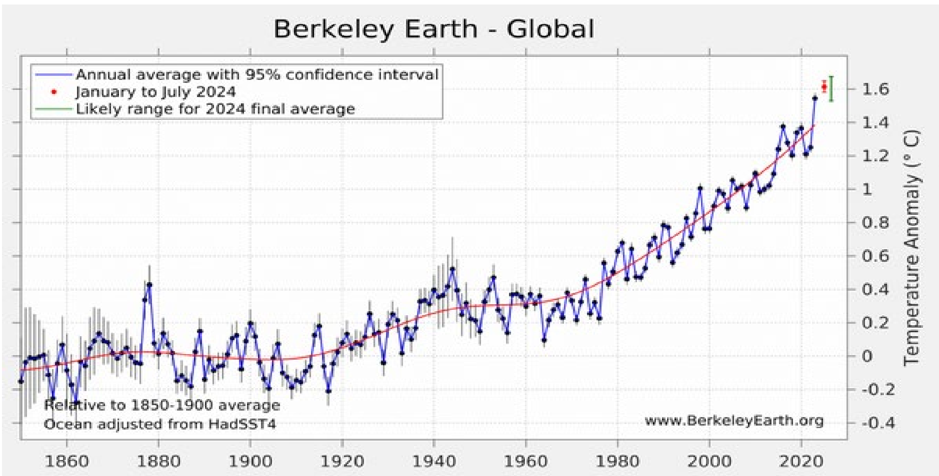


Figure 2: Annual average global surface air temperature anomaly

The above shown rise in global temperature is attributed to a small imbalance in the radiative flows, estimated to be only about 0.26% of the incoming radiation [6]. The Northern Hemisphere summer of 2023 and 2024 began a string of days and months where average global surface air temperatures broke their previous records by substantial margins. Notice that 2023 temperature was much higher than the overall trend (red line), while the red point represents 2024 temperature so far, and the green bar shows an estimated average for 2024 [5].

2.2. Natural and Antropogenic causes of climate change

Global temperature change is the result of many factors that act on different timescales. It can be helpful to break these causes down into those that are human-caused versus those that are natural, as well as those that are "forced" versus those that are "unforced." Forced changes are imposed on the ocean-atmosphere system from some cause outside of the system, like a change in the amount of energy coming from the Sun or extra energy trapped by human emissions of greenhouse gasses like CO_2. However, global temperature can also spontaneously change without being forced to do so. Fittingly, these are referred to as "unforced" temperature changes. Unforced temperature changes come from natural ocean-atmosphere interactions that can rearrange the clouds, sea ice, and the distribution of heat, which results in global average surface air temperature change, Figure 3 [7].

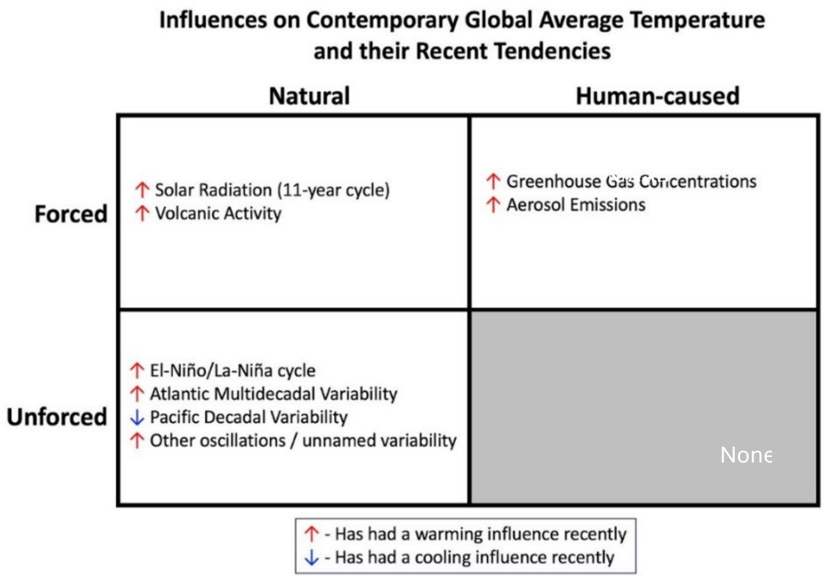


Figure 3: Natural and human causes of recent climate change

All these causes introduce temperature variability on different timescales, but the only cause currently pushing temperatures up on century timescales is the persistent increase in GHG concentrations from human activities like burning fossil fuels. Importantly, though, this upward push is relatively gradual and persistent from year to year, it cannot explain monthly or yearly lurches in temperature like the one currently seen. In order to explain the current spike, it is necessary to look at factors other than the relatively slow increase in GHG concentrations. It turns out that virtually all the other important short-term drivers of global temperature variability may be expected to cause an upward spike at the same time. The recent events, when 1.5°C over preindustrial was achieved, are short term changes in global temperature. They are likely temperature spikes brought about by rare causes, some of thesese have not yet determined. The Paris limit of 1.5°C refers to a long term average over decades and will be crossed some decades into the future. However the recent events do give us an insght of what a permanent 1.5°C will look like. It is important to note that there is a lag time between an increase in CO_2 and CH_4 in the atmosphere and an increase in temperature.

The amount of energy coming from the Sun follows an 11-year cycle. The last trough of activity bottomed out in 2020, and we are on our way to the next peak in 2024-2025–giving global temperatures a small boost. Also, the 2022 eruption of the Hunga Tonga volcano injected large amounts of water vapor (a greenhouse gas) into the upper atmosphere, where it can persist for several years and cause short-term warming, [8]. The spontaneous (unforced) El Niño/La Niña cycle in the Pacific Ocean has the most influence on global temperatures on timescales of months to years. During La Niña years, an unusual amount of heat is sequestered in the Pacific Ocean below the surface, while during El Niño years, that heat is released back to the surface, where it temporarily elevates global temperatures before being radiated to space [9]. Atlantic Multidecadal Variability is also a spontaneous climate driver. Sea surface temperatures in the Atlantic ocean are subjected to an unforced variability, and currently are in their positive phase, pushing global temperatures up. There is a lot more unforced variability than just the named oscillations, as it appears that other components, like those related to Antarctic sea ice, may be acting to push global temperatures up as well.

2.3. Radiative Forcing and Heat Ballance

Sun and outgoing heat by thermal radiation that escapes the Earth. The Earth constantly receives 342 watts/m^2 of energy by the Sun (that is the average, on the equator it's more, on the poles it's less). Of those 342 watts, a total of 235 watts are absorbed, 67 watts by the atmosphere, 168 by the surface, and 77+30 = 107 watts are reflected back into space, Figure 4a [10]. Compared to preindustrial times, GHGs maximally absorb an additional 2.43 watts/m^2, which acts as net anthropogenic forcing with all components taken into account Figure 4b [2].

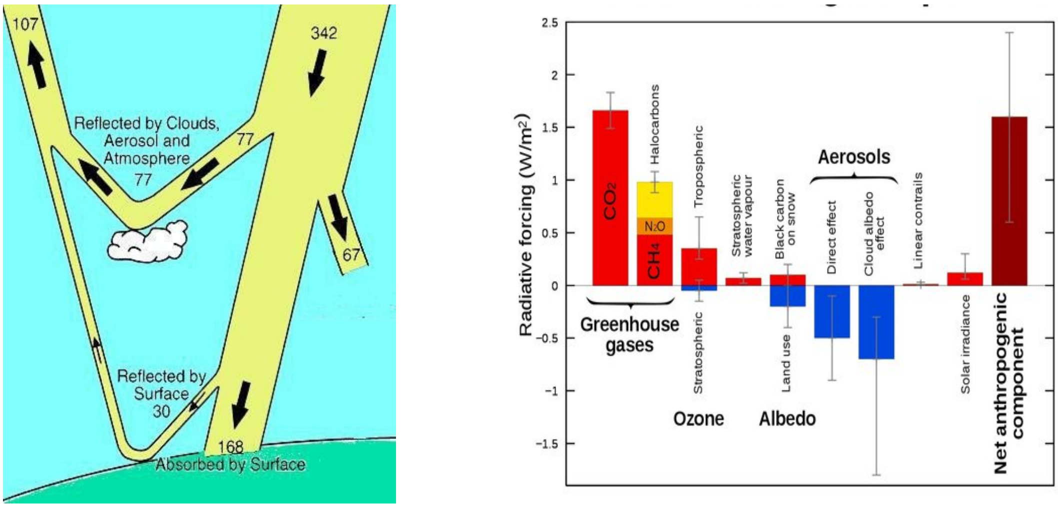


Figure 4: Heat balance (left) and radiative forcing components (right)

2.4. Calculating the Earth's Energy Budget

In general terms ([10]), the energy absorbed by the Earth can be written as:

$$E_i = (1 - a) \times \Omega/4 \tag{1}$$

where 'a' is planetary albedo (0.31, this is the proportion of incoming radiation reflected to space and lost); 'Ω' is the solar constant (solar radiation reaching Earth, about 1367 W/m^2). This is energy delivered at the top of the atmosphere. Ω is divided by 4 because the solar energy is spread over the surface of the planetary sphere assuming the same radius as the circle (area of circle/area of sphere of same radius = 0.25). Again in general terms, the energy emitted by the Earth can be written as:

$$E_O = \sigma \times T^4 \tag{2}$$

where σ = 5.67•10^{-8} J/m^{2}secK^4 and T is temperature in degrees Kelvin. The Earth's temperature reaches a balance (steady state) when the $E_i = E_O$). Under those conditions we can write an equation for planetary temperature:

$$T^4 = [(1 - a)\ \Omega]/4\ \sigma \tag{3}$$

The solution for equation 3 with measured solar flux [10] at the top of the atmosphere yields a value of 254°K (-19.2°C) for average planetary temperature. This estimate is close to observed conditions in the upper part of the troposphere, but of course is much below the average temperature at sea or ground level (about 14° C), which is the main surface of energy absorption and the place of most interest to humanity. Some factor is causing the climate to be recently nearly 42° C warmer than one can explain by calling on the Sun alone.

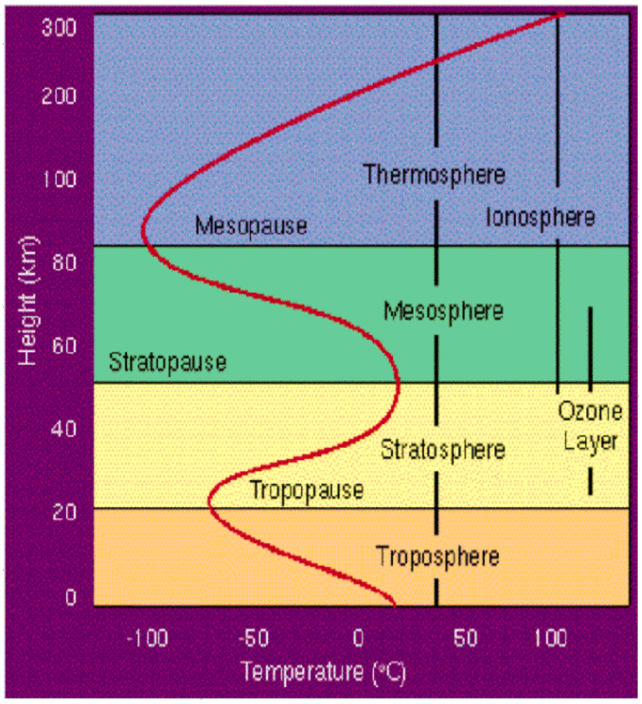


Figure 5: Upward variation of air temperature

There are claims that here is a lot of scientific malpractice at work to make the case that CO_2 and the radiation model is correct, [11]. Climate science violates Newton's laws of heating and cooling ($Q = m \times c \times \Delta T$) as it ignores specific heat '*c*' mass '*m*' and only focuses on radiation as if the atmosphere would be at 0°Kelvin and if not GHGs. The specific heat of air is greater than of CO_2 (1.012 J/g/°C vs 0.844 J/g/°C) and CO_2 adds no heat capacity to air. Air temperature changes during upward cirulation (Figure 5) and when it becomes dry, air cools much faster than humid air which has nothing to do with radiation but with heat capacity. Vapor holds heat with the highest heat capacity of them all (4.1 J/g/°C, [11]). Climate science has convinced the ignorant public that 0.75 g of CO_2 (the amount in a cubic meter of air) at a specific heat of 0.844 J/g/°C is somehow heating the ocean. A cubic meter of air with CO_2 is holding a whopping (0.75×0.844) 0.633 J of energy per degree C. So, essentially, CO_2 is contributing of energy to the surface, and the reality is that CO_2 is cooling the atmosphere. The air would be better off with no CO_2, as the specific heat of air at 1.012 J/g/°C is higher. A cubic meter of air is 1.3 kg at a specific heat of 1012 J/kg/°C+0.75 g of CO_2 at a specific heat of 0.844 J/g/°C adds a whopping 0.633 J of energy to the system. Water has a specific heat of 4.1 J/g/°C. On a kilogram scale, that meter of air above water can not do squat to the 4100 J required to raise a kg of water by 1°C, and the 0.844 J of energy in CO_2 certainly can not have any effect [11]. With the continued rise of gobal temperature such events may become more frequent.

2.5. Predictions of Climate Change in the Future

Climate change refers to long-term shifts in temperatures and weather patterns. Such shifts can be natural, due to changes in the Sun's activity or large volcanic eruptions, but since the 1800s, human activities have been indicated as the main driver of climate change, primarily due to the burning of fossil fuels and generating GHG emissions that act like a blanket wrapped around the Earth, trapping the Sun's heat and raising temperatures. Scientists found that human GHG emissions are warming the world faster than at any time in at least the last two thousand years. The average temperature of the Earth's surface is now more tharn 1.2°C warme than it was in the late 1800s (before the industrial revolution) and warmer than at any time in the last 100,000 years [12]. The last decade (2011-2020) was the warmest on record, and each of the last four decades has been warmer than any previous decade since 1850.

Anthropogenic and natural factors combined are currently pushing global temperatures in the upward direction, and as a result, the years 2023 and 2024 set a new annual record for global warmung being the first to breach the +1.5°C level of warming above preindustrial levels. El Niño might cause further warming so that the year 2024 could be 0.2°C warmer than 2023, and reach +1.7°C [13]. The Figure 6 shows these hypothetical warming levels in the context of projections from climate models driven by long-term increases in GHG concentrations (colors represent different amounts of emissions), but that simulate their own unforced variability. It can be seen that a hypothetical spike up to +1.7°C in 2024 would move temperatures from near the bottom of the envelope in 2021 to near the top in 2024, [14]. Figure 7 shows the same data superimposed on long-term projections by the end of this century based on the same climate models [15]. It shows that the temperature change from human emissions in 2024 would be around +1.35°C. So if 2024 did come in at +1.7°C, it could be that about 80% of that warming was due to human activity, and 20% was due to all the other factors [13].

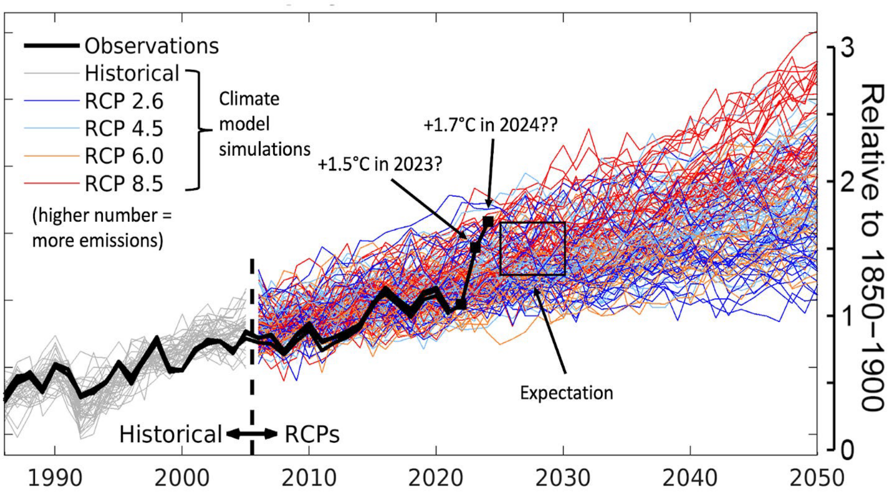


Figure 6: Global temperature rise by 2050 as predicted by climate models

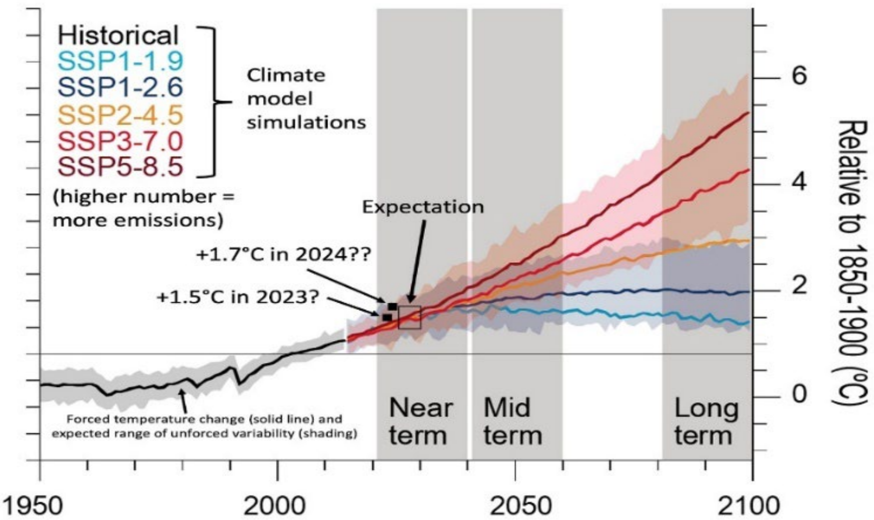


Figure 7: Global temperature rise by 2100 as predicted by climate models

The above figures also show that short-term spikes could not tell much about the long-term trajectory, and the trend would need to last for decades in order to have meaningful implications on long-term warming. Given the unusual coincidence of so many factors pushing in the warming direction at the same time, this fluctuation is not surprising.

3. Global Warming Models and Feed-backs

3.1. The Climate Models as Policy Tools

The climate changes are predicted by global warming models using the Earth's average temperature averaged over the whole planet, and over the whole year. Since climates are different at different places, describing a climate usually includes describing its changes are by the average values of various indicators over multiple years. The models describing climates are much more complicated than global warming models. The most complicated are models desctibing weather, which changes not only place-to-place and year-to-year, but moment-to-moment and predictions of weather are based on current conditions in successively larger regions around the area whose weather is being predicted, so that predictions get less precise the farther into the future they go. None of these models predict all the variations in actual data since these data vary due to many other factors usually not included in the models.

Climate models include assumptions about human behavior, and future average global temperature depends on future human CO_2 emissions, so that detailed models include multiple predictions based on a range of future human actions. As the long term predictions of climate change are still in their infancy, they do not show the details of how changing the average global temperature will be low durng the average winter or hihh during summer in specific regions of the Earth. The models are less able to predict weather variations, and even less able to predict effects on numbers or severities of hurricanes and tornadoes, and, it appears that weather in many different climate zones is getting more variable. However, one kind of climate change models solidly based in both thermodynamics and long term patterns, can represent well the water cycle that transports water from drier areas to wetter areas, and that increasing temperature will *on average* increase this transport.

Scientists expect most of the factors other than increasing GHG concentrations to reverse in the coming years, and the mainstream expectation could be that temperatures would fall back down into the middle of the projections in the 2nd half of this decade [16]. Even if temperatures return to the middle of their climate model projection envelope by the late 2020s, the expected temperatures like those in 2023 and 2024 ould be common in the 2030s. Any drastic change in weather at the regional level associated with this level of global warming would be quite concerning when considering climate impacts over the coming decades.

Basic science is enough to let anyone know that temperatures will continue to rise, and that this will lead to huge impacts in all parts of the world, so it can already reliably predict the existence of the threat. The climate models can help policy makers to know what things will look like if certain actions to reduce GHG emissions are taken or not. The difference between the two should provide them basis for weighing up the various climate policies. Although they are now regularly confronted with evidence of climate change impacts: droughts, heatwaves, wildfires, floods and so on, accurate predictions provide them a peculiar sort of comfort: at least they have some idea of what the outcomes might look like.

Faced with the daunting threat of changing climate, one feels better to know what the future might look like. Bearing in mind an extreme complexity of the climate system, question is whether it is really possible to predict the future climate? There are certainly many people trying to use computer models of the climate system, and in recent years a lot of money is spent in making them ever more detailed. As models become more complex they look increasingly realistic, so it is tempting to believe the predictions will be good. In July this year, a summit was convened in Berlin to discuss Earth Virtualization Engines or “Eve” with the organisers calling for massive investment billions of euros to buy huge new computers. “Eve” will no doubt gain trust of governments and other funders, but is the rush to build bigger and bigger models the best use of resources to guide global response to climate change? [17].

Big computer models provide all kinds of detailed predictions, but the complexity of the systems they are dealing with gives a reason to question whether they actually do that, and even whether more advanced ones ever could do. The problem is to know how close to reality a model needs to make good predictions. A chaotic nature of the climate system means that small differences in the representation of a single item could have a very large impact on something quite distant and seemingly unrelated. Part of the problem is that, as the models become more and more complex, they often look increasingly realistic, so it is very tempting to believe that the predictions will be good.

Climate models are assessed on how well they simulate the past. But climate change is bringing world to a never-before experienced situation, so the past may not be an accurate guide. There is no doubt that the latest climate models are outstanding achievements of computer-based science, but they are not equivalent to reality [18]. They might not represent the real world with all the stunning complexity of Earth’s many interlocking systems, but they might be useful tools for scientific research. Being not meant for weather forecast, climate models are as good guesses in testing a theory against reality (known as “fit test models”) used to see if the theory can predict future events and to estimate if the situation is approximately like the theory is. Well-designed experiments could use models only to get information about the scope of effects different responses could have including the uncertainties and the range of plausible futures.

So, if the models can not give reliable, detailed climate predictions, policy makers should accept to deal with incomplete information. Instead of trying to make the responses just right for the climate of the future, they should seek out resilient and flexible solutions, remedies that will be robust in a wide range of possible climate outcomes. Even though the uncertainties are large, the information is still a useful basis for making decisions. The risk is that investment in ultra-high resolution models could actively undermine a timely response to climate change.

3.2. Feedbacks in the Climate System

The Earth augments solar heating through a response to the Sun's energy. As the amount of water vapor in the atmosphere increases with temperature, warming the Earth adds water vapor to the atmosphere, and adding water vapor to the atmosphere magnifies that warming. Since the water vapor relationship to temperature is exponential (Figure 8, [19]), and under warmer conditions a modest increase in temperature can lead to a large increase in water vapor and associated greenhouse effect. The water vapor response is the primary cause of greenhouse warming on Earth, and it will magnify the warming by CO_2 and other gases. The water vapor effect might sound terminal for the planet Earth as it feeds the progressive warming. However, this warming is balanced by cloud formation, and increases albedo, thus reducing the solar energy that reaches the lower atmosphere and Earth's surface. This cloud effect provides negative feedback on planetary temperature. The formation of clouds depends on water vapor content in the atmosphere and the temperature change with the elevation. The role of clouds in balancing positive feedback from GHGs is complex and the response of cloudiness to changes in GHG concentrations is still not well understood [20]).

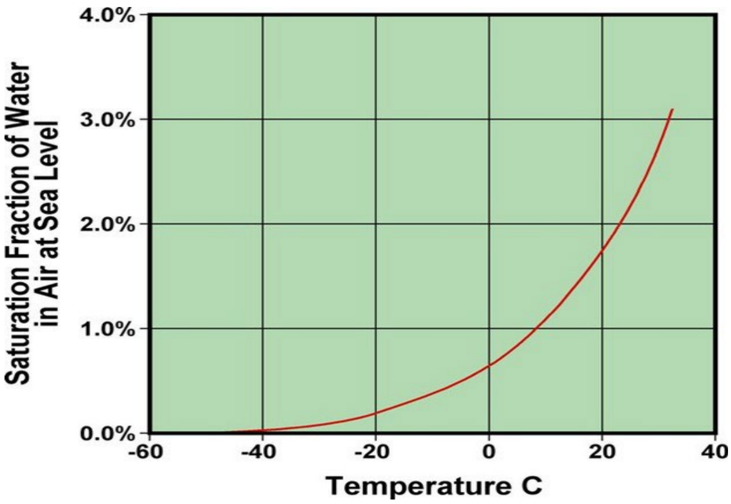


Figure 8: Vapor dew point vs air temperature at sea-level

As atmospheric composition responses to solar warming provide positive feedback on planetary temperature, other responses mitigate change and provide negative feedback. Negative responses could increase planetary reflectivity, so less solar energy is absorbed by Earth; or they might prevent significant changes in atmospheric composition. Dominance of climate/environmental processes by negative feedback would lead to homeostasis, a concept developed by James Lovelock [21]. How much stabilization the Earth's climate gets from negative feedbacks is, at least in part, revealed by the climate history of the past 2 million years during which the Ice Ages occurred and planetary temperature dropped (4–5°C). It is a fact that large climate changes occurred across the globe, and that atmospheric CO_2 concentrations co-varied with the temperature changes (Figure 5). Indeed, the CO_2 variations help to account for 50% fraction of the Ice Age temperature changes [22]. This is what we would expect from positive, rather than negative, feedback processes

One interesting idea ([23]) connects ocean circulation to atmospheric CO_2 content and planetary temperature, so that climate change alters circulation and then circulation can alter climate (a positive feedback). This idea takes us to the Southern Ocean surrounding Antarctica where deep ocean water upwells and returns to the surface circulation system. This deep water is cold, and it contains lots of dissolved carbon. This makes the deep ocean a repository for dissolved carbon. The result of carbon transfer to depth in the oceans is that water is carbon enriched, and when it rises to the surface it will give up a fraction of its carbon load to the atmosphere as it warms. How much CO_2 there is in the atmosphere depends, in part, on the balance of oceanic drawdown and release. With more upwelling, increased volumes of CO_2 could be released to the atmosphere and warming would be accelerated. This could account for the lock step pattern in atmospheric CO_2 and glaciations which we observe and the positive feedback that the climate record implies.

4. Challenging Secrets of the Climate System

4.1. Carbon Badget and How It Changed

In pre-industrial times there was around 120 Gt of carbon taken up by land plants every year and another 120 Gt released back into the air by respiration of plants and all living things that eat plants There is another flow of about 0.8 Gt of carbon carried by rivers into the ocean and about 87 Gt of carbon was absorbed into the oceanAbout 88 Gt of carbon was released back into the atmosphere out of the ocean (1 Gt more than absorbed) from respiration and simple release of dissolved CO_2. these numbers all balanced out evenly more or less and for ten thousand years the carbon stored in the atmosphere remained steady at around 590 Gt. (1 kg of carbon = 3.67 kg of CO_2). The volume of the atmosphere is estimated at $4.431 \cdot 10^{18}$ m^3. At current 420 ppmv, the atmosphere contains $420 \cdot 10^{-6} \times 4.431 \cdot 10^{18} = 1.86 \cdot 10^{15}$ m^3 CO_2. Converted to GtC by a factor 12/24, this leads to $9.31 \cdot 10^{14}$ kg C = 931 GtC, so that 1 ppmv of CO_2 corresponds to 2.22 GtC. (At atmospheric conditions, 1 kmol of gas has a volume of 24 m^3, and 1 m^3 of gas equals 1/24 kmol so that 1 m^3 of CO_2 has a weight of 44/24 kg which corresponds to 12/24 kg carbon, [24]).

After the industrial revolution, the amount of carbon added to the atmosphere is rising every year. In the 1960's was added around 3 Gt of carbon per year and today we are adding around 9.6 Gt of carbon per year [25]. Since 1990, global CO_2 emissions have increased by more than 60%. Global CO_2 emissions from fossil fuels and industry totaled 37.15 billion metric tons ($GtCO_2$) in 2022. Emissions are projected to have risen 1.1 percent in 2023 to reach a record high of 37.55 $GtCO_2$. In addition we are cutting down the forests and clearing land for agriculture, roads and cities which adds another 1.2 Gt of carbon per year. Plants are able to use a bit more and now take up around 123 Gt of carbon [26]. The ocean is presently taking up around 3 Gt of carbon every year and if we immediately stop all emissions the oceans and plants would continue to remove around 5 or 6 Gt per year (declining each year as the CO_2 in the atmosphere reduced) and so in around 150 years the excess CO_2 in the atmosphere might be expected to return to 590 Gt (all things being equal). However the global ocean conveyor formed in the polar seas where cold water absorbs CO_2 before it sinks to the ocean floor and flows into Indian and North Pacific Oceans before returning the North Atlantic. The ocean conveyor takes around 1,000 years to complete one loop [26]. This means that the CO_2 absorbed today will eventually be returned to the atmosphere CO_2 emissions recycled back as the ocean conveyor completes its cycle.

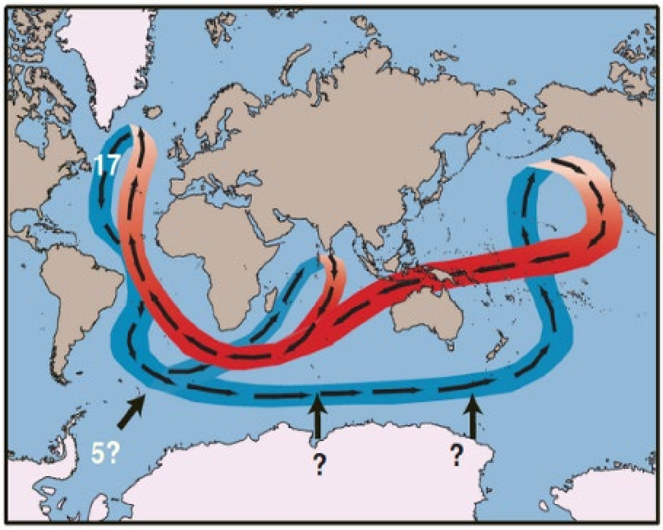


Figure 9: The ocean cinveyor loop

4.2. Why the Earth is Not Cooling Now

Global warming and climate change have always had causes in regular changes of the energy received from the solar radiation due to changes of the Earth's position towards the Sun. According to Mlanković's ice ages theory, the changes of radiation the Earth's surface receives from the Sun changes due to cyclical changes of the shape of the Earth's orbit around the Sun (Figure 10a), as well as of the the tilt of Earth's axis (Figure 10b) and its precession (Figure 10c).

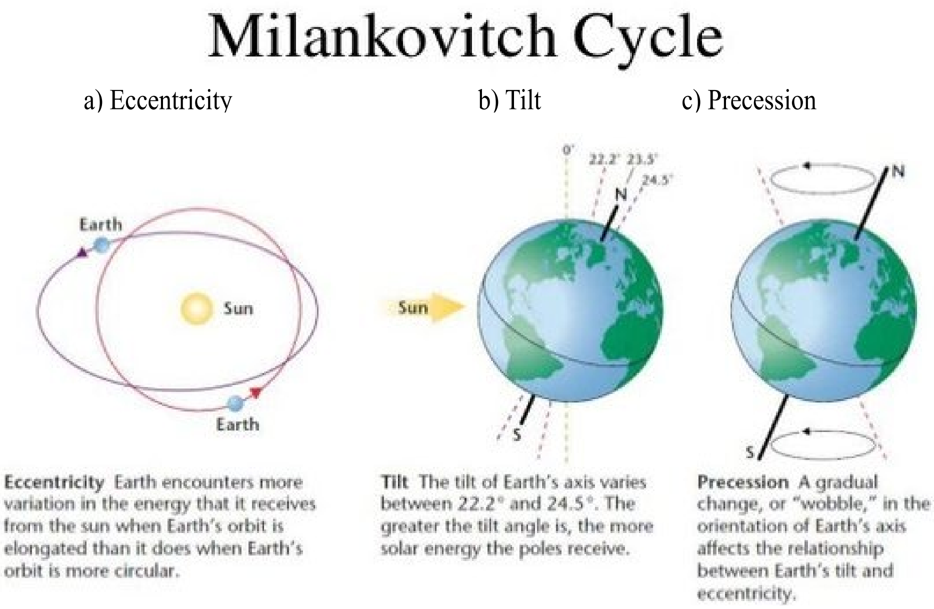


Figure 10: Milanković's cycles of the Earth's rotation;

The Earth encounters more variation the energy that it receives from the Sun when Eart's orbit is elongated than it does when the orbit is more circular. The tilt of the Earth's axis varies between 22.2° and 24.5°, so that the greater the tilt angle is, the more solar energy poles receive. Also, a gradual change (wobble) in thre orientation of Earth's axis affects relationship between Eart's tilt and excentricity of the Earth's orbit while rotating around the Sun.

According to Milanković's cycles theory, the Earth should still be cooling as it has been cooling slowly for over 6500 years [27]. Earth's axis has tilted it measurably away from the source of heat and it should be cooling. Earth's wobble has similarly been conducive to cooling. For over half a century, the current Solar cycle has diminished Earth-warming solar irradiance. However, the Earth warming has continued over the last 100 and more years due to human caused disturbance of the natural carbon cycle by burning fossil fuels, [28].

4.3. Heat Exchange Between Ocean and Atmosphere

The global climate system is also regulated by the energy balance in the oceans and the atmosphere. Global ocean circulation and atmospheric circulation are driven by forces that strive to even out differences in temperature between high and low latitudes. Heat exchange between ocean and atmosphere is an important factor in regional climate patterns. Conditions that influence this balance, such as changes in air and sea temperatures, or cloud and sea ice cover – will thus influence how the climate evolves. On a geological time scale, changes in the shape and location of continents can have strong effects on circulation and heat balance and thus also on global climate. However, given that the continents have been in approximately the same place for the past 500000 years, this is not a factor of any importance for ongoing climate change. On geological time scales, the concentrations of GHGs (especially CO_2) change through natural processes [29]. Volcanos emit CO_2 to the atmosphere. This release is balanced by processes that capture CO_2 in the seabed, and it can be demonstrated in several ways that the increase in atmospheric CO_2 levels since the industrial revolution has been caused by human activities.

The Earth traps most of its energy at the land-ocean surface, so that the atmosphere is heated from below, and the oceans are warmed from above. Much more heat is absorbed at low than at high latitudes because the Earth's surface gradually tilts away from the Sun as moving away from the equator. That tilting spreads the solar energy supply over progressively larger areas of ground or ocean surface, so that each square meter gets less and less heat poleward. At low latitudes the Earth's surface actually absorbs more energy that its upper atmosphere emits to space, while at high latitudes is reverse is true because the latitudinal temperature gradient in the upper troposphere is less than at the surface

5. Motion in the Climate System

5.1. Motion of Energy Within Climate System

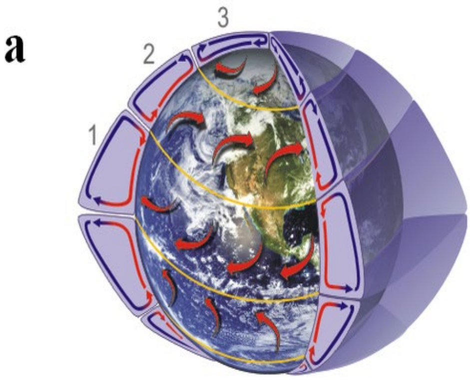
The motion in the climate system is due to both vertical and horizontal energy gradients in the atmosphere and oceans. Because absorbing more energy than is lost at low latitudes, and the reverse closer to the poles, is not sustainable, there has to be a balancing so that temperatures stabilize across the planet, and this requires a transfer of heat from the equatorial region to higher latitudes. The transfer is done through large scale motions in the atmosphere and oceans. Motion (winds and currents) happen because solar heating and heat loss to space create pressure gradients so that wind and water move from high to low pressure conditions, [30].

5.2. Motion of the Air

Heating the bottom of the atmosphere, especially in the tropics, makes the air less dense so it becomes buoyant and rises which makes the atmosphere unstable and leads to air lifting to altitude, especially near the equator. Rising lower density air in the tropics forms the largest vertical motion in the atmosphere (the Hadley Cell) and the rising air from the tropics spreads poleward and loses heat to space by radiation. The cooling causes density to increase and the air sinks, most intensely at about 30° either side of the equator. The downward motion creates a region of higher air pressure at the Earth's surface that balances the area of the low pressure within the equatorial zone. The air pressure gradient along the surface will make the winds blow from mid to low latitude. A pressure gradient also develops poleward of 30 degrees so that winds are driven to higher latitudes as well. From the mid-latitude surface high pressure center, winds are directed north and south. Heating air along the equator lowers its density so that it rises and spreads to the higher latitude and cools by radiating energy to the outer space.

Winds are also generated by the rotation of the Earth. Unlike the northern and southern direction of the winds, there are westward and eastward winds. These winds affect ocean currents. Warm, tropical waters carry heat pole-ward along the east coast of continents; cold water from the poles is forced toward the equator along the west coast. Warm surface currents can carry heat well away from the tropics, bringing temperate climates to areas nearer the poles than the equator. Deeper currents are driven by a combination of Earth’s rotation and temperature differences between the tropics and the poles. Cold, dense melted water from the icecaps flows underneath warmer surface waters towards the equator.

Figure 11 ([30]) presents the motion of the air at different latitudes. Figure 11a shows the atmospheric circulation once the Coriolis effect is incorporated with the vertical circulation cells, with produces the dominant surface winds. Figure 11b shows an equator to pole (meridional) view of the circulation cells in the atmosphere, which broadly divide the Earth into climate belts. The combination of wind and ocean currents redistributes heat and moisture across Earth’s surface. Around 60% of the solar energy that reaches the earth is redistributed around the planet by atmospheric circulation and around 40% by ocean currents [30]. The flow of the winds is made trickier by the fact that the motion is happening over a rotating surface as the Earth spins to the east and the speed of that rotation at the surface is fastest at the equator and drops to zero at the poles. The winds blowing to lower latitude get left behind as they rotate eastward at a lower speed than the the speed of surface they are traveling over which increases towards the equator, and, due to the Coriolis Effect, the winds blowing to the equator turn towards the west. Winds blowing poleward of the high pressure center near 30 degrees lattude veer to the east as their eastward motion outstrips that of the surface they are flowing over. In this way a steady flow from west to east (the Westerlies) is created at about 45 degrees latitude [30].



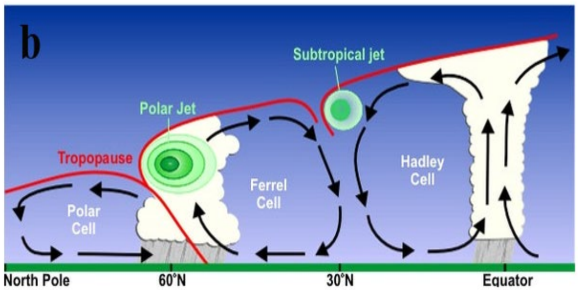


Figure 11: Atmospheric circulation along latitudes

Poleward of 60° N and 60° S, the winds generally blow westward and equatorward as the polar easterlies. In the northern polar regions, where water and land are interspersed, the polar easterlies give way in summer to variable winds. Combined, the vertical and horizontal movements of the winds serve to collect heat in tropical regions and transfer it poleward as one part of the planetary energy balancing act.

5.3. Polar Vortex

A circumpolar vortex, or simply polar vortex, is a large volume of cold air, rotating around both of Earth's polar regions, [31]. The term "vortex" refers to the counter-clockwise flow of air that helps keep the colder air near the Poles. The polar vortex always exists stable (Figure 12a) near the poles, but weakens in summer and strengthens in winter. During winter in the northern hemisphere, the polar vortex will expand, sending cold air southward with the jet stream (Figure 12b). Those light blue arrows are the "jet stream" - very fast high altitude winds that form at the boundary of the vortex and the warmer southern air. When they are fast, they generally result in the polar vortex remaining stable and cold air remains near the polar regions, but when very hot air from the tropics comes north, it slows down the jet stream. Although this allows hot air to push much further north, it also means that the cold air in the polar vortex pushes south, often reaching as far as the southeasts and the air temperatures become record low. Now, these sorts of system are rare (once in about every 40 years [32]). Situations like these might become more frequent in warmer climate conditions faced by the current society.

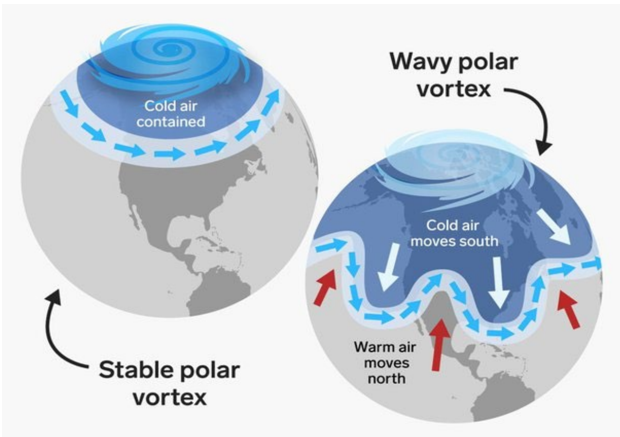


Figure 12. Stable (a) and wavy (b) polar vortex

5.4. Precipitation Patterns

Solar energy heats water to evaporate by consuming the heat of evapotarion, rises up as steam and, when cooled down, it condenses by releasing the heat of condensation, thus forming clouds and water droplets fall as precipitation. At the same time as driving evaporation and precipitation patterns, sunlight is creating winds. As warm air moves upward, colder air from neighboring areas rush in to fill the void left behind. At the equator, the Earth receives greater exposure to the Sun's rays where both air and extensive bodies of water warm under the influence of the Sun. The warm air that rises in the tropics is wet. Sunlight causes water to evaporate from plants, soils, and bodies of water. Some of the cold, dry rising air flows to the poles, where it absorbs moisture creating the cold climates of the polar regions. Some of the air is drawn back toward the equator, and some is drawn toward the pole as part of a new air mass. At latitudes around 60° north and south, the air again rises, cools and releases precipitation.

Whereas most coastal regions experience high levels of precipitation, continental interiors are typically arid. Distant from large bodies of water, these areas lack sources of water to recharge moisture in the air. In addition, any air masses reaching them tend to have already discharged any moisture that they carried. Some rain shadows create extremely arid, desert-like conditions. With modest changes in winds, patterns of precipitation do not change much, but result in dry areas becoming drier (generally throughout the subtropics) and wet areas becoming wetter, especially in the mid- to high latitudes.

There is a direct influence of global warming on precipitation. Increased heating leads to greater evaporation and thus surface drying, thereby increasing the intensity and duration of drought. However, the water holding capacity of air increases by about 7% per 1°C warming, which leads to increased water vapor in the atmosphere [33]. The atmospheric and surface energy budget plays a critical role in the hydrological cycle, and also in the slower rate of change that occurs in total precipitation than total column water vapor, Figure 13.

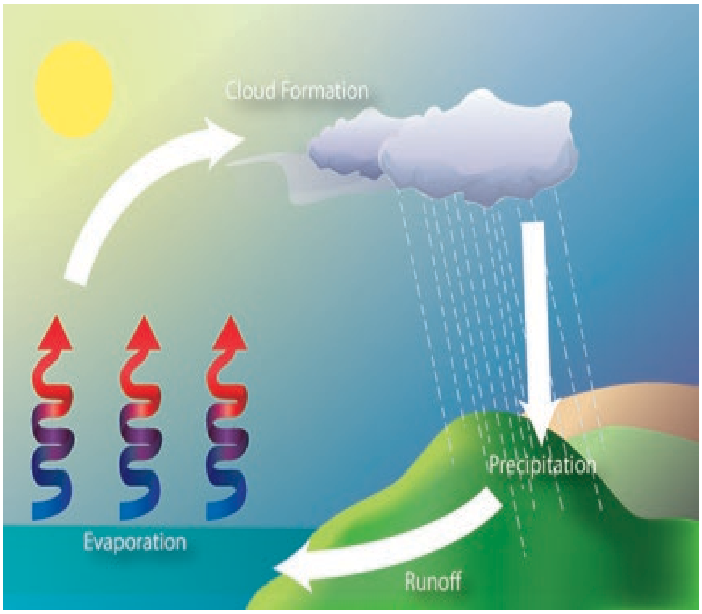


Figure 13: Precipitation cycles

Molecules are more closely packed together when are cold than when they are warm, which makes warm air and water less dense than cold air and water. This difference in relative density causes heat to rise. These water molecules rise to become part of the air; because the air is warm and less dense, there is sufficient room for water molecules within the air mass. But as the air gains altitude it cools, reducing density and space for water. The water molecules condense to form clouds and fall as precipitation.

In tropics and subtropics, precipitation patterns are dominated by shifts as the sea surface temperature change with El Niño [34]. Also, the volcanic eruption of Mount Pinatubo in 1991 ([35]) led to unprecedented drop in precipitation and runoff and to widespread drought, as precipitation shifted from land to oceans and evaporation faltered, providing lessons for a possible geoengineering. Most models simulate such a precipitation that occurs prematurely and too often, and with insufficient intensity, resulting in recycling that is too large and a lifetime of moisture in the atmosphere that is too short, which affects runoff and soil moisture.

5.5. Motion of the Sea Water

The winds blowing over the oceans move water by friction on the surface. As the water begins to move, the currents veer westwards if going to lower latitudes and easterwards if going poleward due to Coriolis Effect. Surface ocean currents are driven in circles called gyres [36]. The largest of these, the subtropical gyre, fills the middle of all oceans and rotates such that poleward flow is on the western side of the basin. Heat transfer from low to high latitudes is via the western boundary currents of the oceans (like the Gulf Stream in the North Atlantic, [30]). This is another part of the planetary energy balancing act. The Gulf Stream is what keeps Europe warm but it also puts the ice on Greenland building it up. The Gulf Stream is the part of this current system that goes from the Gulf of Mexico towards northern Europe. It is run by the heat of the Sun over the oceans and also driven by the electro-capacitive interaction with the Solar Wind. Stopping it requires the Sun to stop pushing it, which happened to a great extent in “The Little Ice Age”.

The ocean circulation is responsive to climate conditions [37]. The surface currents of the oceans operate in a relatively thin upper layer of the sea which is heated by the Ssun. This heating is kept relatively close to the ocean surface because warming water makes it less dense and more resistant to sinking or mixing downwards. The result is a barrier, called the thermocline, which develops particularly at lower and mid-latitudes and that separates surface waters from the deep ocean. The boundary, marked by a rapid downward temperature drop, usually occurs within a few hundred meters of less of the surface. Below it, the greater mass of the oceans (down to an average depth of about 3800 m, [30]) is cold and isolated from the winds. Since the light surface water would be resistant to mixing downwards, the deep sea is in motion initiated where the oceanic water column breaks down and surface water sinks due to processes which raise its density. The primary cause of water column destabilization is extreme cooling over a large depth range combined with sea-ice formation. Making ice, leaves behind a brine which is quite salty and so quite dense and heads for the deep sea. .

The deep water masses develop at high latitudes, particularly in the Atlantic basin [38]. Deep waters born in the Atlantic spread to the other ocean basins using the circum-planetary highway that surrounds Antarctica. This seaway serves as the roundabout connecting all the oceans allowing deep Atlantic water to spread heat gradients as these drive wind and deep ocean flow. The winds provide upward draw on deep waters thanks to the Coriolis Effect. Along the eastern sides of ocean basins and around Antarctica winds blow such that Coriolis veering drives surface waters oceanward, and the result is a process called Upwelling which causes deeper water to rise and replace the water pulled away from the shore [39]. Interestingly, deep ocean circulation can also feedback into climate change to alter the way it develops. Figure 14 compares vertical circulation in the Atlantic ocean in the modern age (a) and modeled for the last ice age (b), as redrawn from Sigman *et al.* 2010 [40]. Centers for sinking surface water are located at either end of the Atlantic basin. The circulation in Antarctic ocean in the modern times (A) produces intermediate depth waters (SAMW, AAIW) which fill the mid-depths of the ocean; and bottom water (AABW) which fills the deep ocean southern basin. When sinking, surface waters in the North Atlantic (NADW) fill the deep northern basin. In Ice Age times (B), the equivalent of AABW likely was more dense than at present (colder, saltier) and more isolated from the atmosphere by sea-ice. It formed its own circulation cell more separated from that of the North Atlantic which was relatively less dense and so circulated at shallower depths [37]). The solar warming will lead to decreasing density and a return of water to the upper ocean circulation system. Deep water flow gives a third dimension to the ocean's response to the planetary temperature gradient. The cycle of surface and deep ocean circulation, is vital to the distribution of heat, chemicals and life in the oceans. It is sensitive to anything which will alter seawater densities in regions where sinking occurs ([41]), or any process which changes winds and ocean-atmosphere interaction in upwelling areas.

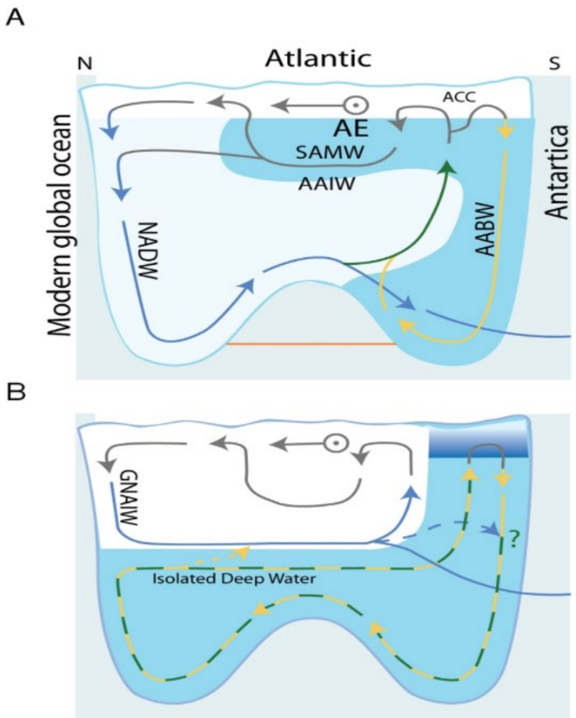


Figure 14: Vertical circulation in the Atlantic ocean in modern age (a) and modeled for the last ice age (b)

5.6. Ocean Currents

Ocean currents are driven by a combination of Earth's rotation and temperature differences between the tropics and poles. Ocean currents vary on depths in which they flow, with denser pole melted waters flowing beneath warmer surface waters towards the equator. Unlike the northern and southern direction of the winds described above, there are westward and eastward winds. Winds are also generated by the rotation of the Earth. These winds affect ocean currents. Warm, tropical waters carry heat pole-ward along the east coast of continents: cold water from the poles is forced toward the equator along the west coast. Warm surface currents can carry heat well away from the tropics, bringing temperate climates to areas nearer the poles than the equator Figure 15 presents the global oceanic circulation at these three depths [41].

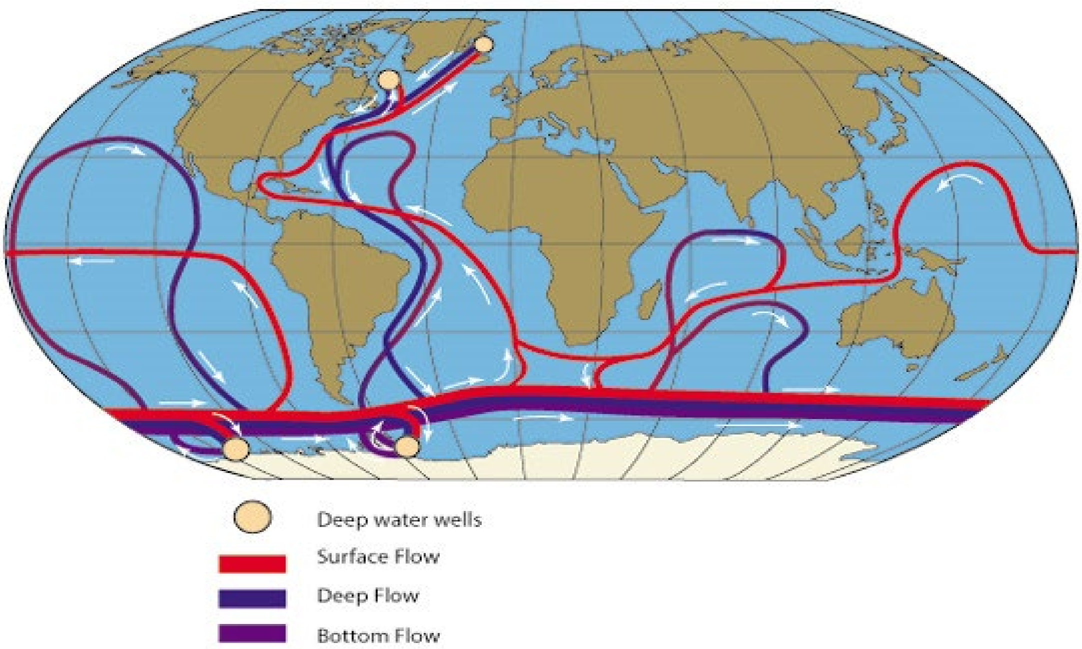


Figure 15: Global oceanic circulation

Deeper currents are driven by a combination of Earth's rotation and temperature differences between the tropics and the poles. Cold, dense melted water from the icecaps flows underneath warmer surface waters towards the equator. The combination of wind and ocean currents redistributes heat and moisture across Earth's surface. Around 60% of the solar energy that reaches the Earth is redistributed around the planet by atmospheric circulation and around 40% by ocean currents, [41].

Proximity to large bodies of water influences climate on a regional scale. Coastal areas experience less seasonal variation in their climates than do continental interiors. Winters are milder, summers cooler, and the temperature swing between daytime high and nighttime low is much less extensive. This is partly due to the high heat capacity of water, i.e. its ability to hold heat for very long periods of time (8 to 10 centurys, [26]) and to release that heat when the atmosphere cools, and partly due to redistribution of heat by ocean currents.

5.7. El Niño-Southern Oscillation (ENSO)

A simple model of the coupled Pacific Ocean and atmosphere, forced with orbital insolation variations, suggests that seasonal changes in insolation can produce systematic changes in ENSO behaviour [40]. This model simulates a progressive, somewhat irregular increase in both event frequency and amplitude due to the Bjerknes feedback mechanism ([42]) and ocean dynamical thermostat [43]. Snapshot experiments conducted with some coupled GCMs also reproduce an intensification of ENSO between the early Holocene and the present, although with some disagreement as to the magnitude of change. Both model results and data syntheses suggest that before the mid-Holocene, the tropical Pacific exhibited a more La Niña-like background state. In palaeoclimate simulations with GCMs, ENSO teleconnections robust in the modern system show signs of weakening under mid-Holocene orbital forcing [44].

Under normal conditions, warm water pools in the western Pacific, but during an El Niño event, the heat covers most of the tropical Pacific. During an El Niño event, the trade winds decrease, and the surface currents follow suit. Rather than pooling in the western Pacific, warm water covers much of the ocean surface in the tropics. This redistribution of heat leads to evaporation, condensation, and precipitation in the eastern Pacific and is responsible for atypical flooding in North America, South America, even Europe, and for drought conditions in Australia, Indonesia, and parts of Africa. Scientists are currently working to more reliably predict El Niño events, in hopes of ameliorating their negative impacts on human and non-human populations [45].

Temporal changes in climate at small scales tend to be predictable: seasons occur consistently from year to year. However, changes may occur when oceanic currents and movement of air masses are disrupted. The best-known example of this phenomenon is the El Niño-Southern Oscillation, a global climate phenomenon that emerges from variations in winds and sea surface temperatures over the tropical Pacific Ocean. [46]. Figure 16 shows how ocean and atmospheric circulation change during a Niño event.

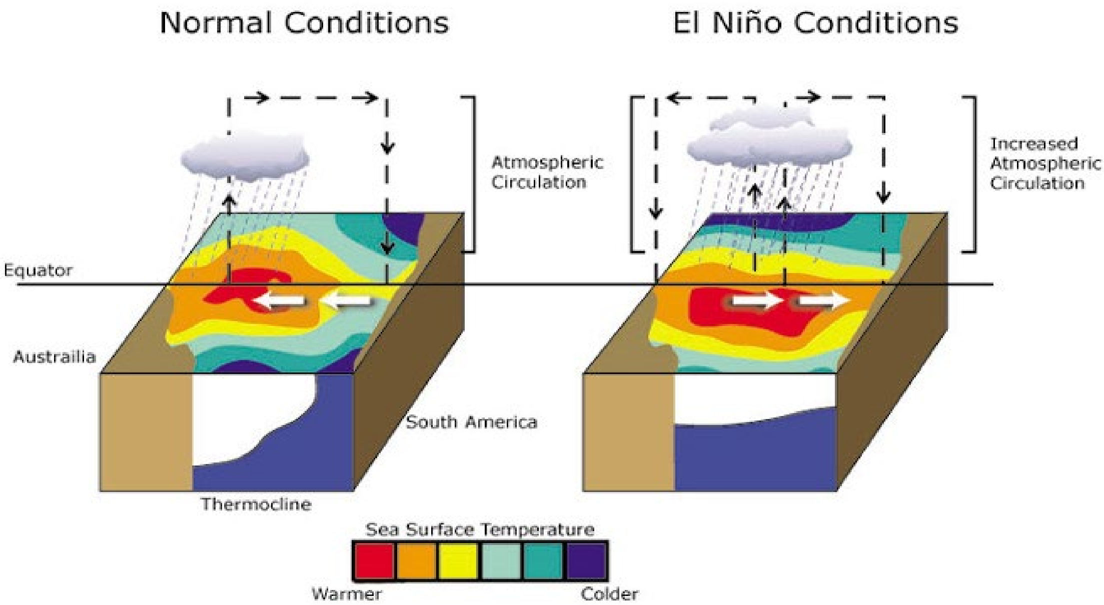


Figure 16: El Nino Southern Oscillations

5.8. Global Warming and Ocean Cooling

Humans are now facing the dominant effects of climate change, with about 98% of the globe much warmer than decades ago. It may seem quite unusual that, under these cicumstances, the Atlantic ocean is cooling down during the global warming when global average temperatures of the oceans have increased rapidly since the 1970s (in line with the rapid increase in atmospheric temperatures) and continue to increase rapidly Figure 17 [47].

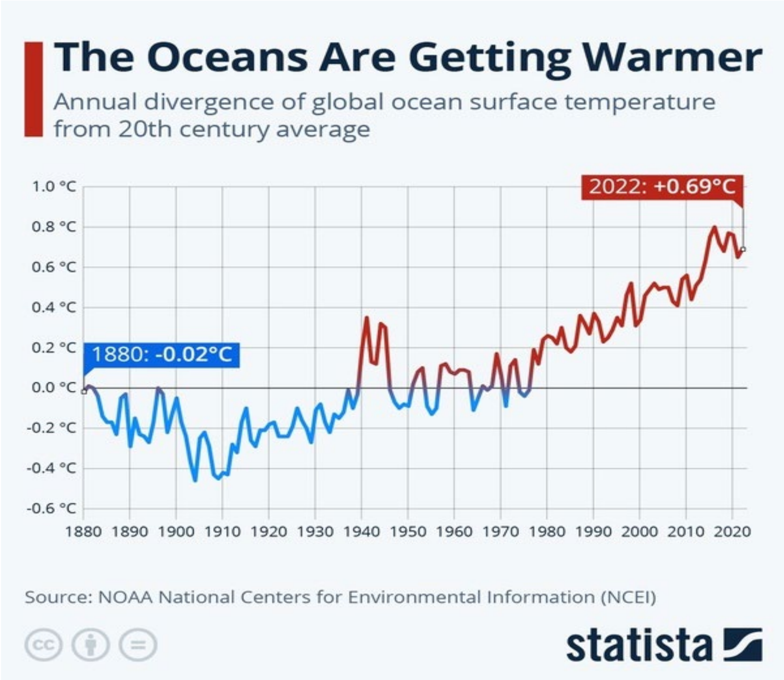


Figure 17: Annual divergence of global ocean surface temperature from 20th century average

Despite the fact that temperatures reached new highs in the Atlantic ocean, scientists found that the Ocean is cooling down, but they are not quite sure why, and the reason behind the cooling remains a mystery to them. There is also cooling in the eastern Pacific due to equatorial upwelling, and parts of Antarctica are also cooling, although there is warming overall. A few areas will cool from time to time, and natural changes continue, just as they have for billions of years. In case of Atlantic ocean, scientists are prone to believe that La Niña is replacing an El Niño and that That could be due to going from El Niño to La Niña the ocean surface cools [48]. Figure 18 ([49]) shows that a decline in Niños was from about 2000 to 2020 and they are becoming more active again. This year El Niño turned to La Niña in June.

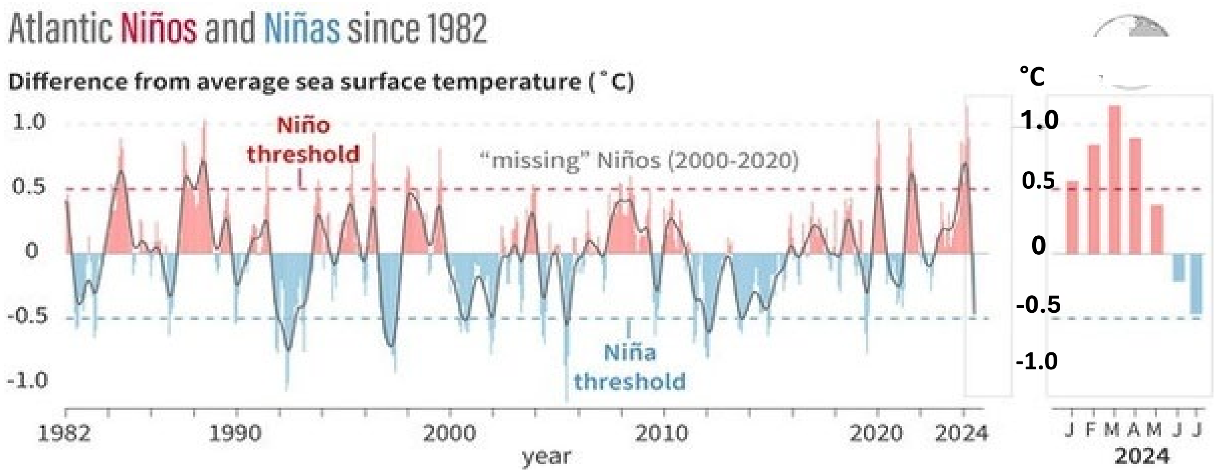


Figure 18: Atlantic Niños and Niñas since 1982 and during 7 months in 2024

The recent cooling in part of the Atlantic Ocean is not caused by anthropogenic climate change, although it is now the dominant force in climate change, and about 98% of the globe is warmer than 50 years ago. 2023 had over a year of record high global ocean temperatures. but the eastern equatorial Atlantic has cooled rapidly during the last months. Scientists knew that the temperature rise in 2023 would be historic, but were surprised by how much. It just means that scientists can not understand yet all of the factors involved and that scientific models are incomplete because it is almost impossible to include everything with perfect precision.

Overall, ocean global average temperatures have increased rapidly since the 1970s (in line with the increase in atmospheric temperatures) and continue to increase rapidly, Figure 19 [50]. At early July 2024, temperatures are back to about where they were in 2023, a record year.

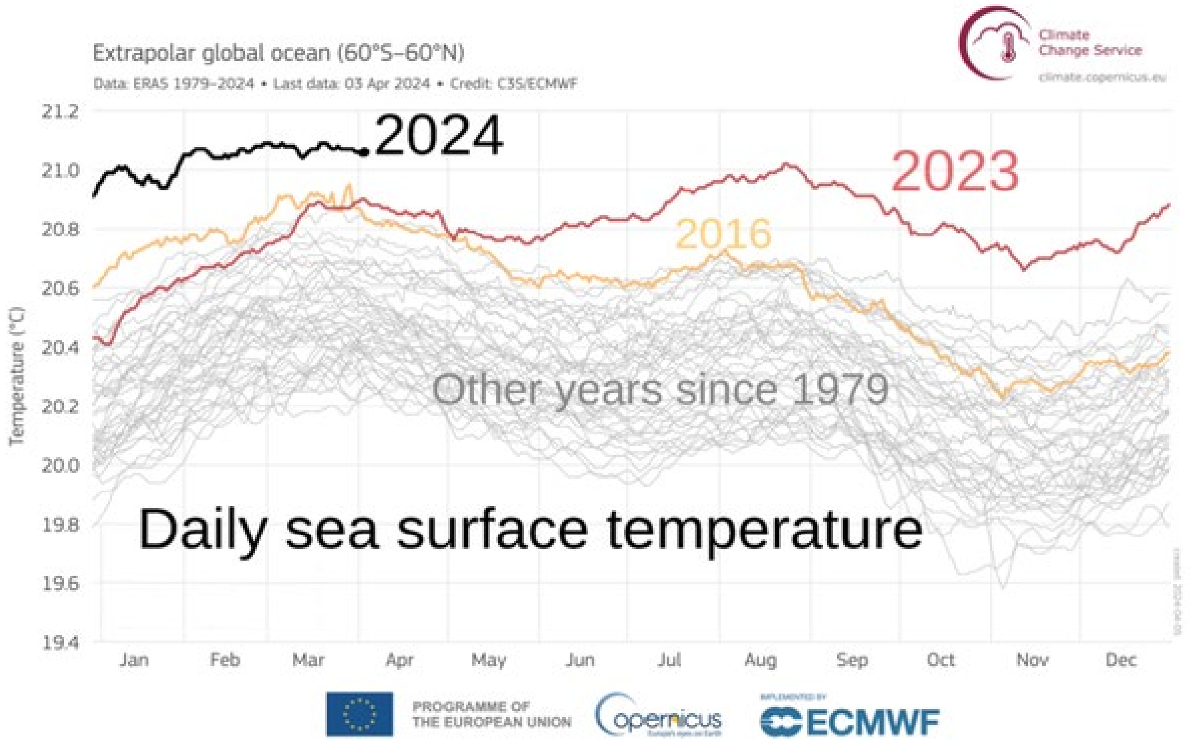


Figure 19: Daily sea surface temperatures since 1979

6. Conclusion

The global climate is a very complex system of systems, with literally millions of factors constantly interacting with each other. It is therefore practically impossible to have all of them modelled so precisely as to simulate the real situation irrespective of the size and power of supercomputers used. In addition to the number and complexity of the processes that need to be modeled, an insurmountable obstacle is represented by interactive positive feedback loops, some of which have not yet been studied nor observed at all. Even when models manage to simulate the known past of climate change with sufficient precision, neither supercomputers nor any other help can provide the ability for models to accurately simulate future climate [51].

On the other hand, to let society know precisely how to oppose unacceptable climate changes and to prepare for survival in the conditions of a changed climate, the models would have to provide precise information about the future climate conditions, which they have not demonstrated yet that can do. One of the reasons for this disadvantage may be methodological approach itself, which is dominated by statistical averaging every data in space and time instead of dynamic simulation of processes that constantly change by motion and interact with each other with a multitude of positive and negative feedback loops.

From a comprehensive review presented in this paper it could become evident to what extent the five components of the climate system interact with each other through all forms of movement and exchange their mass and energy, all being driven both by the energy received from the Sun and the portion of this energy prevented by the atmospheric greenhouse effect to escape into outer space. A closer look to what and how the processes within the climate system develop, it may become challenging for the thermal engineers to join the majority of active experts less avare of how helpful may be the thermal and hydraulic sciences in their efforts to better understand the nature of climate change and reduce risks from the new climate reality.

References

[1] Baede A., The Climate System: an Overview, IPCC WG I Assessment Report, New York, 2000
[2] Mesarović, M., Scientific Uncertainties Feed Skepticism on Climate Change, Thermal Science, Year 2015, Vol. 19, Suppl. 2, pp. S259-S278
[3] The Balance of Power in the Earth-Sun System NASA, www.nasa.gov, Approached, Sept.1, 2024
[4] Harte, J., Consider A Spherical Cow: A Course in Environmental Problem Solving, University Science Books, 2023, p 376
[5] July 2024 Temperature Update - Berkeley Earth www.BerkeleyEarth.org, Approached September 1, 2024
[6] F.S. Chapin, III et al., Principles of Terrestrial Ecosystem Ecology, 23 DOI 10.1007/978-1-4419-9504-9_2, © Springer Science+Business Media, LLC 2011
[7] Global Temperatures are Spiking The Breakthrough Institute. Oct 23, 2023
[8] Owen, R., Atmospheric effects of Hunga Tonga eruption lingered for years, Eos, 105, https://doi.org/10.1029/2024EO240379. Published on 22 August 2024.
[9] El Niño–Southern Oscillation, Wikipaedia Approached 30 Augudt 2024
[10] Harte, J., Consider A Spherical Cow: A Course in Environmental Problem Solving, University Science Books, 1988, p 283
[11] Hill et al. Heat capacity, the ocean, and our weather, Section 4.2, Oceanography, University of California, Davis
[12] https://www.un.org/en/climatechange/what-is-climate-change, Approached September 1, 2024
[13] The Climate Report, The Liberal Patriot and The Breakthrough Institute, Berkeley, Oct 23, 2023
[14] Hawkins, E., Warming Stripes, Climate Lab Book, May 14, 2024
[15] Climate Change 2021: The Physical Science Basis. Contribution of WG I to the Sixth Assessment Report of the IPCC Chapter 4 Figure 4.2, IPCC New York 2021
[16] Tollefson, J., Is it too late to keep global warming below 1.5 °C?, Nature, 21 Nov. 2023
[17] Stainforth, D., The big idea: can we predict the climate of the future? The Guardian, 2 Oct. 2023
[18] Cowtan, K et al, "Robust comparison of climate models with observations using blended land air and ocean sea surface temperatures", Geophysical Research Letters, vol. 42, pp. 6526-6534, 2015
[19] Shiel, C.L et al, A Note on the Relationship between Temperature and Water Vapor in Quasi-Equilibrium and Climate States, Goddard Earth Sciences and Technology Center, University of Maryland, Baltimore Baltimore, February 7,2003
[20] Dale, A., C. Fant, K. Strzepek, M. Lickley, and S. Solomon, Climate model uncertainty in impact assessments for agriculture: A multi-ensemble case study on maize in sub-Saharan Africa, Earth's Future, 5, (2017) 337–353, doi:10.1002/2017EF000539
[21] Lovelock J. E, Geophysiology, the science of Gaia, Reviews of Geophysics, May 1989
[22] https://doi.org/10.1029/RG027i002p00215, Approached August 22, 2024,
[23] Hausfather, Z., Explainer: How the rise and fall of CO2 levels influenced the ice ages, Carbon Brief, 2 July2020
[24] Toggweiler J.R. & Key, R., Thermohaline Circulation Chapter in Ocean Circulation, In book: Encyclopedia of Atmospheric Sciences December 2003(pp.1549-555)
[25] Rörsch, A. Et al, Global warming and the accumulation of carbon dioxide: A Critical Consideration of the Evidence, Energy & Environment, Vol. 16, No. 1, 2005
[26] Tiseo, I., Annual global emissions of carbon dioxide 1940-2023, Statista, Jun 13, 2024
[27] Sabine, C. L, et al, The Oceanic Sink for Anthropogenic CO2, Science 305(5682)2004, 367-371
[28] Milankovitch (Orbital) Cycles and Their Role in Earth's Climate, NASA Science Editorial Team, Feb 27, 2020
[29] Why Milankovitch (Orbital) Cycles Can't Explain Earth's Current Warming, NASA Science Editorial Team Feb 27, 2020
[30] Mesarović, M., Global warming and other climate change phenomena on geological time scale, Thermal Science, Year 2019, Vol. 23, Suppl. 5, pp. S1435-S1455
[31] Loubere, P. The Global Climate System. Nature Education 3(10) 2012:24
[32] https://www.weather.gov/safety/cold-polar-vortex, Approached 02.10.2024
[33] A Series of Rare Disturbances in the Stratosphere, NASA Earth Observatory, August 5, 2024
[34] Trenberth, K.E., Changes in precipitation with climate change, Inter-Research, 2011, vol. 47, No.1-2, pp. 123-138
[35] L'Heureux, M., What is the El Niño–Southern Oscillation (ENSO) in a nutshell? NOAA, Climate.gov, Published May 5, 2014
[36] The Cataclysmic 1991 Eruption of Mount Pinatubo, Philippines, U.S. Geological Survey Fact Sheet 113-97
[37] http://www.classzone.com/books/earth_science/terc/content/visualizations/es2401/es2401page01.cfm?chapter_no%7C%7C#eq$%7C%7Cvisualization, Approached 26.Aug.2024
[38] Rahmstorf, S., The thermohaline ocean circulation - a system with dangerous thresholds? Climatic Change, 2000. 46: p. 247-256
[39] http://svs.gsfc.nasa.gov/vis/a000000/a003600/a003658/ Approached 13.September 2024
[40] http://www.classzone.com/books/earth_science/terc/content/visualizations/es2405/es2405page01.cfm?chapter_no%7C%7C#eq$%7C%7Cvisualization Approached 26.Aug.2024

[41] Clement, A. C, et al,. Suppression of El Niño during the Mid-Holocene by changes in the Earth's orbit, Paleocenography and Paleoclimatology, 4 May 2010
[42] Rahmstorf, S., Thermohaline Ocean Circulation. In: Encyclopedia of Quaternary Sciences, Edited by S. A. Elias. Elsevier, Amsterdam, 2006.
[43] Bjerknes, J. Atmospheric teleconnections from the equatorial pacific. Journal of Physical Oceanography, 97(3), 163-172. Tellus, 18(4), 1969. pp. 820-829.
[44] Clement A.C. et al., An Ocean Dynamical Thermostat, Journal of Climate, Volume 9,1996, pp.2190-2196
[45] Otto-Bliesner, El Niño/La Niña and Sahel precipitation during the middle holocene, Geophysical Research Letters, 1999 - Wiley Online Library
[46] L'Heureux, M. What is the El Niño–Southern Oscillation (ENSO) in a nutshell? NOAA, Climate.gov, Published May 5, 2014
[47] https://en.wikipedia.org/wiki/El_Nino_Southern_Oscillation, Approached 24 August 2024
[48] NOAA National Centers for Environmental Information, Washington, 2024
[49] Wilson M., Scientists say the Atlantic ocean is cooling down and they don't know why, Spaces, August 21, 2024
[50] Atlantic Niña on the verge of developing. Here's why we should pay attention, NOAA, www.Climate.gov, Approached September 3, 2024
[51] Copernicus: May 2024, streak of global records for surface air and ocean temperatures continues https://www.washingtonpost.com/climate-environment/2024/01/09/record-hot-year-2023-global-temperatures/ https://en.wikipedia.org/wiki/Sea_surface_temperature, Approached 28 Aug.2924
[52] Z. Hausfather, H.F. Drake, T. Abbott, and G.A. Schmidt, Evaluating the Performance of Past Climate Model Projections, Geophysical Research Letters, vol. 47, 2020.