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CLIMATE SYSTEM IN A NUTSHELL: AN OVERVIEW FOR UNDERSTANDING CLIMATE CHANGE

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ABSTRACT

Along the Earth planet's history (~4.5 billion years) events of climate change have occurred but not so fast as in the last hundred years. This literature review summarizes the main aspects of the physics of the climate to explain in a simple way the natural forcings that affect the climate system and lead to climate change. But, only natural forcings are not enough to justify the increase of ~1.1°C in the global average of air temperature since the pre-industrial period. In this sense, the contribution of human beings to climate change is highlighted and it is shown that their activities are the main responsible for the fast increase in the average air temperature.

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INTRODUCTION

Recently, the researcher Yuval Harari declared that Covid will not eliminate human beings but global warming can do it (Mali, 2021). Moreover, Harari asked the question: "If we cannot cooperate globally to deal with a problem like Covid, how are we going to be able to cooperate to deal with climate change?" His speech highlights two important problems that we are facing: the negative impact of climate change on our lives and no global cooperation by the stakeholders to apply measurements to decrease the causes of global warming. Although events of climate change have occurred along the Earth planet's existence (~4.5 billion years), they were associated with natural forcings. In the last hundred years, the changes in the air temperature have occurred so fast that are incomparable with other past periods of climate change in Earth's history. The warming of the planet has been exacerbated since the beginning of the first industrial revolution in ~1760-year. So, we have here a great "hint" for explaining climate change in the current years. The issue of climate change is a constant target of the media, but without causing great sensitivity either in the population or in decision makers. Regarding society, perhaps this is linked to a lack of understanding about what the greenhouse effect is and its effects on the climate system. In order to contribute to the dissemination of knowledge, this study aims to provide a global view of the climate system to make understandable these highlighted points.

The target audience for this study is the Earth Science educators, undergraduate students of all areas, and high school teachers since they can disseminate the knowledge presented here. This review is organized as follows: Section 2 "Components of the Climate System" introduces the idea of the climate system and their components. Section 3 "Natural Climate Change and Variability" is dedicated to discuss the differences between climate variability and climate change as well as and the natural forcings of climate. Section 4 "Anthropogenic Climate Change" presents the contribution of human beings to climate change and, finally, in Section 5 "Climate Modeling and Projections for South America" the main concepts in climate modeling and some projections for South America are presented. Final comments are giving in section "Conclusion".

COMPONENTS OF THE CLIMATE SYSTEM

Let's start defining weather, climate and system. Weather is the state of the atmosphere at a particular time and place. Weather is the result of the developing and decaying of atmospheric systems such as frontal zones, cyclones and others (IPCC, 2001). Climate is the average weather in terms of the mean and its variability over long periods. Climate varies on space and time. Spatial variations are related to the latitude, distance to the sea, vegetation, topography or other geographical factors of a specific region. Time variations are in seasonal, annual, decadal or longer time-scales (IPCC, 2001). Time variations are a response of some drivers that will be explained in the next sections. System is an entity whose components interact according to the laws of physics, chemistry, and biology. Then, the climate system (Figure 1) corresponds to the interaction among their components: atmosphere, hydrosphere, cryosphere, lithosphere and biosphere (Ruddiman, 2008; IPCC 2007, 2013, 2021). As a detailed description of these five components is provided in books of Fundamental Meteorology, such as Pidwirny (2006), Ynoue *et al.* (2017) and Ahrens and Henson (2021), or in books of Physics of the Climate, such as Peixoto and Oort (1992), Ruddiman (2008) and Hartmann (2015, 2016), in the next subsections only the main characteristics of each component of the climate system are presented.

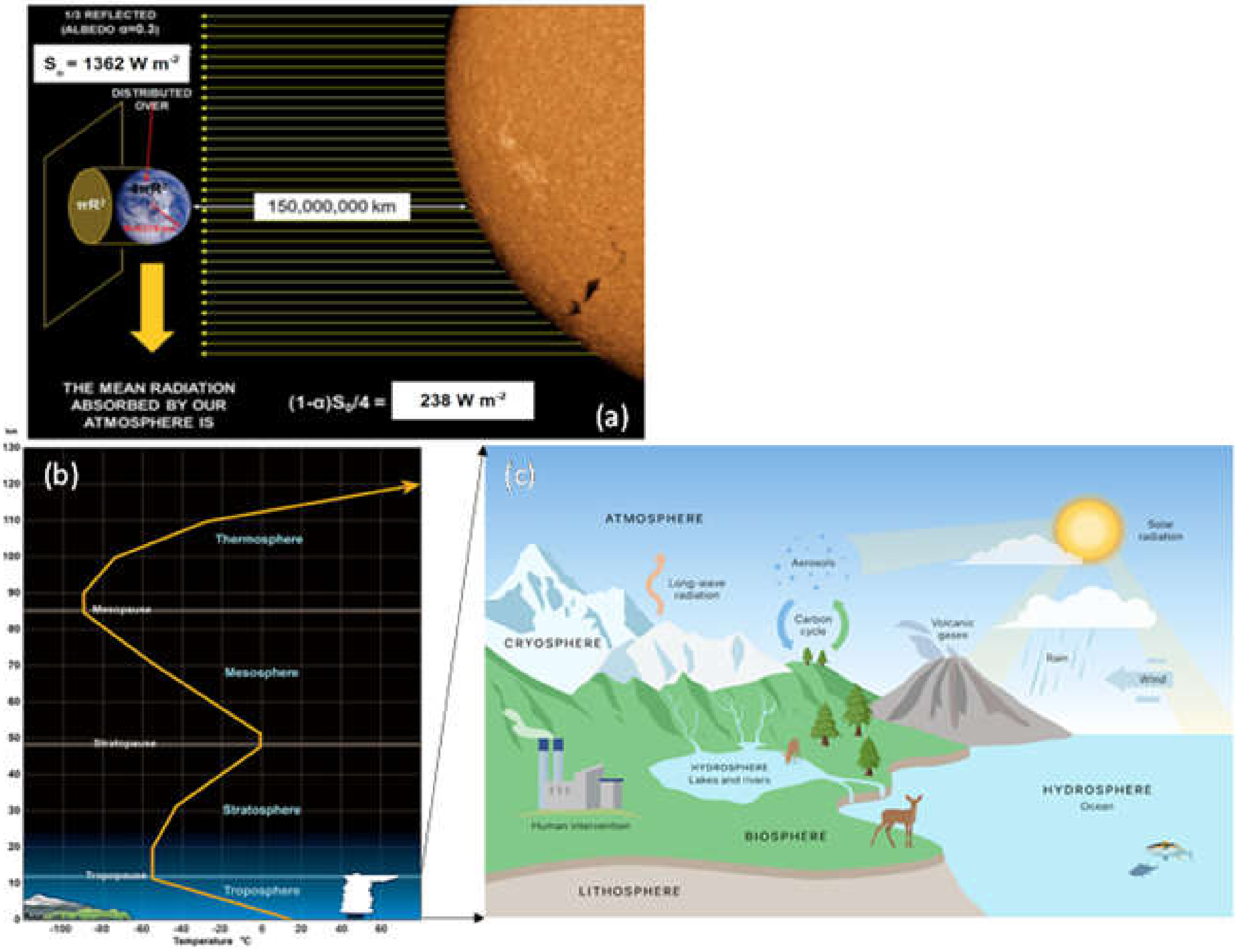


Figure 1 (a) Basic radiative interactions of the Earth-Sun system (adapted from Brunetti and Prodi, 2015), (b) layers of the atmosphere defined by the mean temperature (source: NOAA https://www.weather.gov/jetstream/layers) and (c) general view of the components of the climate system and their interactions (source: https://www.wren.co/blog/posts/what-factors-affect-climate). Panel (b) is a representation inside the troposphere

Atmosphere: The atmosphere is an envelope of gases and particles (called aerosol) surrounding the Earth and there is no well-defined altitude to limit the upper border of the atmosphere (Lagzi *et al.* 2013). The atmosphere becomes less dense as the distance from the Earth's surface increases. Around 90% of the atmosphere constituents are within 15 km of Earth's surface, which corresponds to only 1/400 of the radius of Earth (Trenberth, 2020), while around 99% of the air constituents are located in the lower 30 km's layer (Lagzi *et al.* 2013). The vertical structure of the atmosphere can be defined based on the air temperature of the layers (Figure 1b) in troposphere, stratosphere, mesosphere and thermosphere. In the troposphere, the temperature decreases from the surface to around 11 km height. Moreover, this layer contains about 80% of the total mass of the atmosphere, nearly all water vapor and dust particles (Lagzi *et al.* 2013). Troposphere is also the layer where the majority of weather events occur (fronts, cyclones, anticyclones, thunderstorms etc.). From ~11 km height until ~50 km height, the ozone, which is found in the atmosphere composition, absorbs solar radiation (ultraviolet wavelength), and the temperature increases characterizing the stratosphere. Most of the atmospheric studies are concentrated on these two atmospheric layers. While the thermal structure of the atmosphere is composed of four layers, for the chemistry composition it is only divided in two layers. The layer from the Earth's surface up to an altitude of about 80 km is the homosphere, which is separated from the heterosphere by a thin transition layer called turbopause (Lagzi *et al.* 2013). The gases present in the heterosphere can be classified as permanent or of variable concentrations. Nitrogen (N; 78.08%), oxygen (O_2; 20.95%) and argon (Ar; 0.93%), which correspond to about 99.96% of the heterosphere composition, are permanent gases. Carbon dioxide (CO_2), ozone (O_3), methane (CH_4) and water vapor (H_2O) are examples of gases with variable concentrations (which are also referred to as trace gases). For example, H_2O can have spatial variability and is also concentrated in the troposphere while great concentration of O_3 is present in the stratosphere. CO_2, O_3, CH_4 and H_2O, although in a small concentration, are essential for the maintenance of life, as they contribute to the so-called greenhouse effect. To define the greenhouse effect, we need to have a basic understanding of solar and terrestrial radiation. Figure 1a shows that the distance Sun-Earth is ~150000000 km. As farther is one planet from the Sun, less energy it receives in its surroundings. In the case of Earth, the energy received is 1362 W m^{-2}, which is called solar constant (S_o). But only a portion of the planet receives energy because the other is in a shadow region. The part of the Earth facing the Sun can be approximated by the area of a circle (□ r^2). Since the Earth is a sphere, we must calculate the ratio of the area of the circle (□ r^2) to that of the sphere (4 □ r^2), which results in ¼. Thus, the energy intercepted by the atmosphere is ¼ S_o, which corresponds to ~340 W m^{-2}. On the other hand, the climate system does not receive all this energy, since there is albedo

(□), responsible for reflecting around 30% of the incident energy back into space (Figure 1a). Consequently, the energy received in the climate system is (1-□) S_o / 4, which is ~ 238 W m^{-2}. The Sun and the Earth emit in two distinct bands of the electromagnetic spectrum leading to different wavelength (□) maximum (if you are not familiarized with these terms visit https://imagine.gsfc.nasa.gov/ science/toolbox/ emspectrum1.html). The Sun emits centered at 6000 K (□ = 0.5 µm) and the Earth at 288 K (□ = 9 µm). Note that the Sun is much more energetic than Earth and in consequence the Sun emits solar energy with shorter wavelength (shortwave radiation) than Earth, which emits longwave radiation. However, the Earth has an energy balance because the energy absorbed is equal to the one emitted into space. But the described situation does not consider the Earth's atmosphere. In this situation, the mean temperature of the planet is -18 ^{o}C, which is not suitable for life. Around the 1900-year, the Earth mean temperature was 13.7 ^{o}C; how to explain this difference compared to -18 ^{o}C? It is explained by the Earth's atmosphere which causes a greenhouse effect. The greenhouse effect is a natural process that has existed since Earth's formation (Figure 2a).

able to absorb this energy and reemit in all directions, including the surface. The energy re-emitted to the surface constitutes the greenhouse effect (Figure 2a). This additional energy received by the surface allows the mean temperature of the planet to be proper to life. Even with the greenhouse effect, there is a surface energy balance and an atmospheric energy balance indicating that the incoming energy in the climate system is equal to the outgoing energy into space. The energy gained at the surface is provided directly by the Sun (51 units) and by the greenhouse effect (96 units) totalizing 147 units (Figure 3b). The surface releases 111 units as infrared radiation that is absorbed by the atmosphere, 6 units that escape into space, 23 units as latent heat flux (evaporation) and 7 units as sensible heat flux (conduction and convection), which corresponds to 147 units. So, there is a perfect budget at surface. Considering the atmosphere, it receives 19 units directly from the Sun, and 141 from the surface (111 units is infrared radiation, 23 units is latent heat flux and 7 units is sensible heat flux). Then, the energy gained by the atmosphere is 160 units. The atmosphere releases 96 units to the surface and 64 units to space, totalizing 160 units. Therefore, the atmosphere budget is also closed.

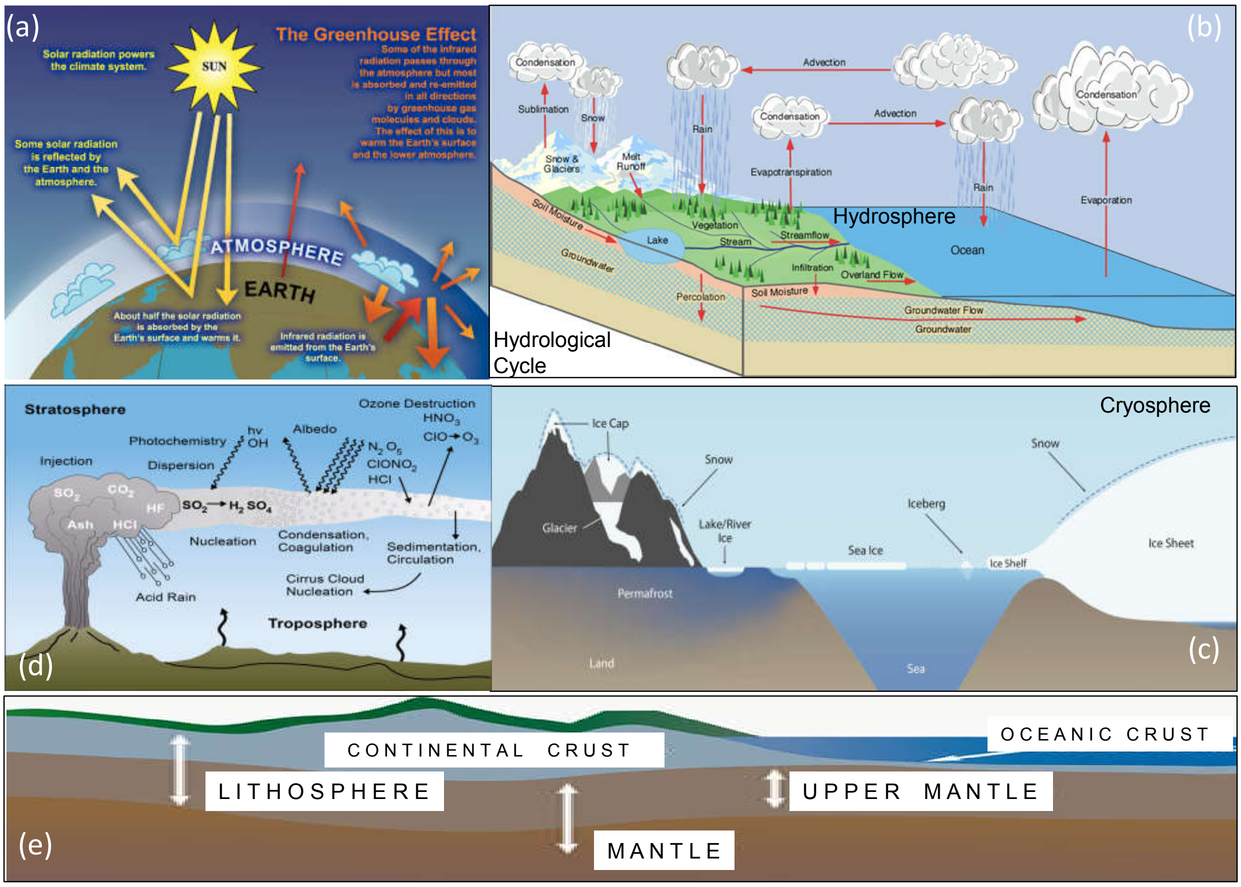


Figure 2(a) Schematic diagram of the natural greenhouse effect (source: IPCC, 2007, https://archive.ipcc.ch/publications_and_data/ ar4/wg1/en/faq-1-3-figure-1.html); (b) hydrosphere and hydrological cycle (source: Pidwirny, 2006, http://www.physicalgeography. net/fundamentals/8b.html; (c) components of the cryosphere (source: Snow, Water, Ice and Permafrost in the Arctic. Arctic Monitoring and Assessment Programme (AMAP), https://cryoconnect.net/cryosphere/); (d) volcanic gases: the conversion of sulfur dioxide (SO_2) to sulfuric acid (H_2SO_2) has the most significant impact on climate (cooling) (source: https://www.usgs.gov/media/ images/volcanic-gases-react-atmosphere-various-ways-conve), and (e) lithosphere (source: https://isaacscienceblog.com/2019/03/ 31/the-lithosphere/)

If we consider the 340 W m^{-2}, which is intercepted by Earth, as 100 units of energy, 30 units are reflected into space (albedo), only 19 units are absorbed by the atmosphere and 51 units reach the surface. Great part of the solar energy reaches the surface because the atmosphere constituents are not able to absorb shortwave radiation (Figure 3a). Then, the surface becomes warmer and heats, through different physical processes (evaporation, conduction, convection and radiation), the air layers above. One of these physical processes is the longwave radiation emission (infrared radiation). Now, the trace gases, such as CO_2, CH_4 and H_2O (also called greenhouse gases), are

The energy balance shown in Figure 3 represents the climate system previously to the industrialization era. The problem facing the planet is that anthropogenic actions have contributed to increasing the concentration of greenhouse gases, therefore, increasing the greenhouse effect and, consequently, the mean temperature of the planet. Indeed, the mean temperature today is 1.1^{o}C higher than in 1900-year (IPCC, 2021). This warming corresponds to a storing of energy in the climate system, which is an imbalance of the energy budget. The energy budget imbalance has been shown in the literature (e.g., Stephens *et al.*, 2012) and is about 0.17 units, which corresponds to 0.6 W m^{-2}. In a nutshell, here is the physical explanation of climate change. Details about the greenhouse gases emissions by anthropogenic activities are discussed in Section “Anthropogenic Climate Change” 4. The state of the atmosphere is influenced by numerous processes involving not only the atmosphere but the other components of the climate system as it will be shown in the following subsections. For this reason, Trenberth (2020) mentioned that the atmosphere is the most volatile component of the climate system.

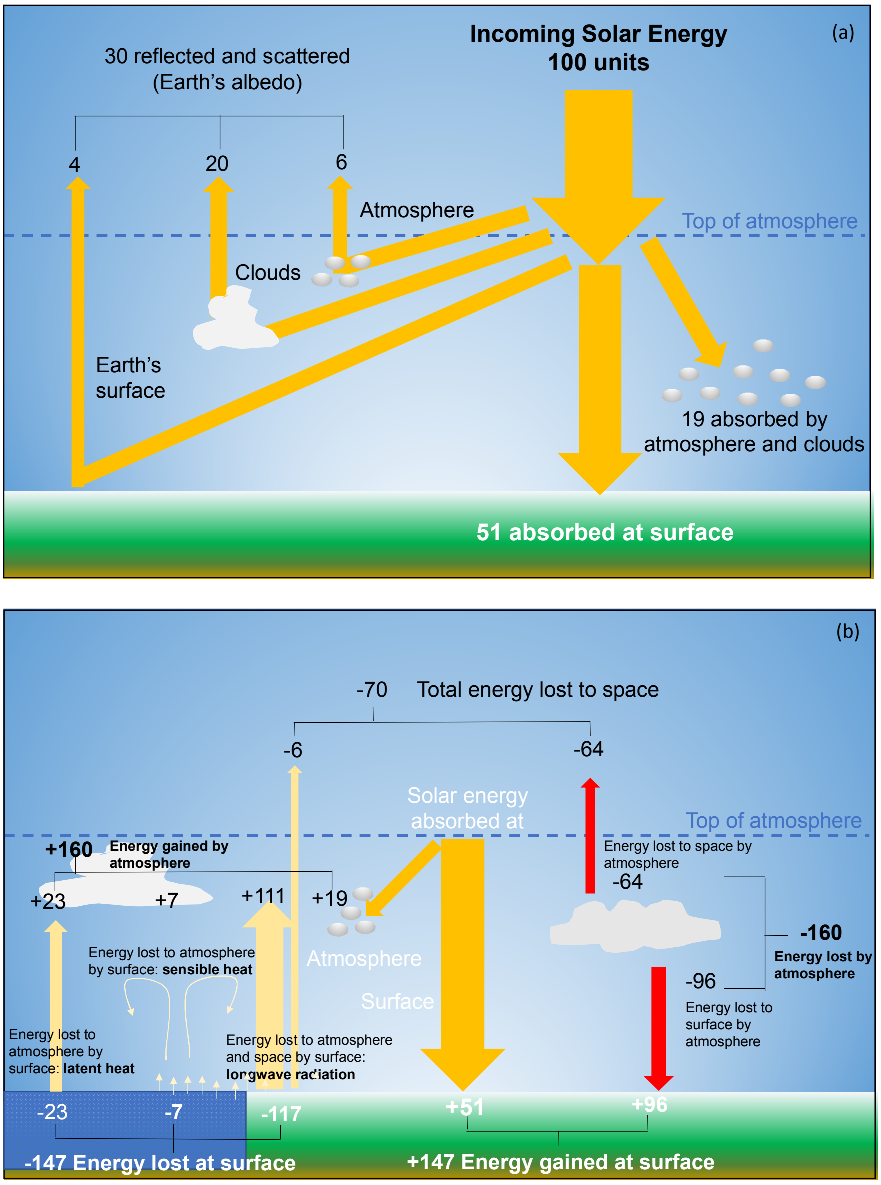


Figure 3 (a) Solar energy absorbed at surface and (b) surface and atmosphere global energy balance

Hydrosphere: The hydrosphere consists of the water in the liquid phase. The liquid water is found on, in and above the Earth’s surface. Considering 100% of liquid water, 96.5% composes the oceans and only 2.5% is freshwater (needed for life). Moreover, water covers more than two-thirds of the surface of the planet (Kauffman, 2015). The movement and storage of the liquid water in the climate system is called the hydrological cycle. In this cycle, the liquid water can change its phase, for example, to vapor during the evaporation process. Figure 2b, obtained from Pidwirny (2006), illustrates the hydrological cycle. One start point to explain the water movement is the evaporation of the surface water. To convert liquid water to vapor, it is consumed energy (latent heat), which is released in the atmosphere when condensation occurs - needed for the cloud formation. Precipitation (liquid water and/or ice crystals) is produced by the clouds and the water that reaches the Earth’s surface can evaporate, transpire by the plants, infiltrate or runoff for a river, lake or ocean. Then, the cycle goes on. Note that the precipitation can occur at the same place where the water has evaporated or in a distant place since the winds transport the air masses into the atmosphere (Bengtsson, 2010; Koutsoyiannis, 2020). Another important fact is that the water phase change is extremely important for transferring energy as in a vertical column of the atmosphere (ascendant movements) as for remote places (horizontal transport for the winds). For example, one of the most important tropical atmospheric systems, the Intertropical Convergence Zone (ITCZ), has the contribution of (a) evaporation for its development and (b) by the moist air transported by the trade winds (Bengtsson, 2010). While in the atmosphere, the winds are important to redistribute heat from tropical to polar regions, in the oceans this function is of the ocean currents. There are two types of oceanic currents: driven by winds and driven by density contrasts caused by salinity and thermal gradients. This second type of current is called thermohaline circulation (Harari, 2021).

Cryosphere: The cryosphere is the component of the climate system formed by water in solid form which includes glaciers and ice sheets, sea ice, lake and river ice, permafrost, seasonal snow, and ice crystals in the atmosphere (Figure 2c). The great polar ice sheets are located in Greenland and Antarctica (Marshall, 2011). The cryosphere has a crucial role in the climate system due to its high surface reflectivity (albedo), i.e., making a large fraction of the solar radiation back into space. Moreover, the cryosphere stores and releases latent heat, affecting the seasonal cycle of the surface temperature, and is a good insulator since it prevents heat loss from the underlying surface (land or ocean) towards the cold atmosphere in winter (Goose *et al.,* 2010). Cryosphere also has a great influence in driving the thermohaline circulation in the deep ocean. Moreover, changes in the ice volume stored on land can directly impact the mean sea level (visit this site https://climate.nasa.gov/blog/3002/sea-level-101-part-two-all-sea-level-is-local/ to know more about the causes of the changes in the mean sea level).

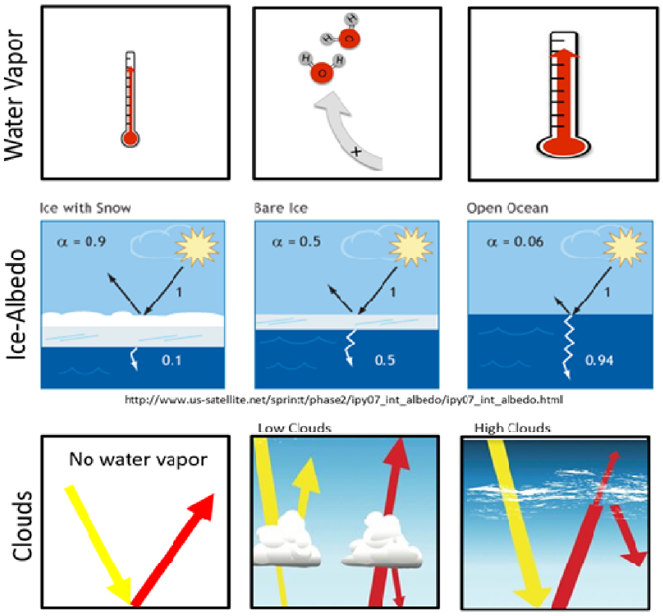
Lithosphere: The lithosphere consists of the crust (oceanic and continental) and the uppermost mantle (Figure 2e). Therefore, the lithosphere depth ranges from 80 km up to 200 km below the Earth's surface. It has a rich chemical composition due to the higher number of minerals: approximately 2000 (Reddy, 2017). As the lithosphere is a reservoir of water and heat, it plays an important role in the water and energy surface budges and, therefore, in the climate system. Many surface-atmosphere interactions can occur through heat transfer by conduction, convective and radiative (infrared radiation) processes, and water transfer by evaporation. Soil moisture is a major player in surface-atmosphere feedback since soil moisture is the limiting factor in evapotranspiration (Nicholson, 2015). It has been shown that summer soil moisture anomalies affect the probability of subsequent rainfall occurrence in the mid-latitudes (Nicholson, 2015). Moreover, the continental lithosphere is a store for carbon, which has been added and reactivated by episodic freezing and re-melting throughout geological history (Foley and Fischer, 2017). Volcanic eruptions can also impact the atmosphere. During eruptions, huge amounts of gases, aerosols and ash are injected into the atmosphere. According to the United States Geological Survey (https://www.usgs.gov/natural-hazards/volcano-hazards/volcanoes-can-affect-climate), ash has little impact on climate change, on the other hand, volcanic gases like sulfur dioxide can cause global cooling (Figure 2d), while volcanic carbon dioxide has the potential to promote global warming.

Biosphere: The biosphere refers to all organic, living life on Earth (animals, plants, fungi etc.). Each type of vegetation on the land surface has a different albedo that causes a critical influence on climate (Goosse, 2015). For example, if one natural vegetation is changed by a specific crop, the albedo in that place will change. The biosphere also impacts the hydrological cycle in different ways: by the evapotranspiration of the plants, by the water storage in soil covered by vegetation that prevents the runoff compared to the bare surface facilitating the evaporation etc. (Goosse, 2015). Through the contribution of the biosphere, there are the biogeochemical (term used in reference of all of the naturally occurring materials, processes, and relationships operating in an area) processes/cycles. One of the most important biogeochemical processes is photosynthesis, which is part of the short-term carbon cycle (on the order of years; Mackenzie, 1999). Carbon dioxide in the atmosphere is removed from the air by terrestrial and oceanic plants (forest, grass, algae etc.). They remove 14% of the atmosphere's total carbon every year (Mackenzie, 1999). However, much of this quantity returns to the atmosphere during the respiration and decay of the plants. The process of injecting and removing carbon dioxide into the atmosphere is a complex cycle and has different temporal scales. The reader can find a detailed explanation of this and other biogeochemical cycles in Mackenzie (1999).

Feedback Effects: The previous paragraphs presented the components of the climate system and introduced the idea that there are a lot of feedback mechanisms among them, i.e., the output of one component can modify other components and be influenced by them (such as looping). So, the feedback mechanisms are also radiative forcings. The term forcingmeans that there are factors that drive or cause changes in the climate system and as a response occurs climatic changes. IPCC (2013) defines a radiative forcingas a measure of the net change in the energy balance in response to a perturbation. The energy balance of the Earth can be affected by three ways (IPCC, 2007): (a) changing the incoming solar radiation, (b) changing the albedo and (c) changing the greenhouse gas concentrations. Climate has a response to these changes through the feedback mechanisms that can either amplify (positive feedback) or diminish (negative feedback) the effects of a change in the climate **(**Figure 4). Although there are a lot of feedback mechanisms, here we describe only three of the most important ones for the climate (Kitchen, 2014; Hartmann, 2016):

Water vapor (positive feedback): an increase in surface temperature enhances the air capacity to hold water vapor, then the amount of water vapor in the atmosphere increases. As water vapor is a greenhouse gas, it leads to further surface warming.

Ice-albedo (positive feedback): in the case of a warmer planet, the ice cover is diminished, which decreases the albedo and leads the ice and snow surfaces to melt, exposing the darker and more absorbing surfaces below. One interesting fact is that the poles are warming in a faster way than the other planet regions. This, in part, is associated with the atmospheric circulation that transports warm and moist air and greenhouse gases to the poles. One small change in the temperature leads to the snow melting to decrease the local albedo and warming the place. This is also occurring in the top of mountain glaciers like the Himalayas (Sabin *et al*., 2020).



http://www.us-satellite.net/sprintt/phase2/ipy07_int_albedo/ipy07_int_albedo.html

Figure 4. Examples of feedback mechanisms: water vapor (top), ice-albedo (middle) and clouds (bottom). Low clouds contribute to increasing the albedo while high clouds contribute to increasing the greenhouse effect

Clouds: the net radiative effect (cooling or warming) of clouds depends on their physical properties such as cloud particle size, ice or liquid water etc. (NASA, 1999; Schneider *et al*., 2019; Murray *et al*., 2021). Low and thick clouds contribute to the reflection of solar radiation (they are formed by a lot of water droplets) leading to a cooling of the Earth's surface. On the other hand, high and thin clouds allow the transmission of incoming solar radiation but intensify the greenhouse effect, therefore warming the Earth's surface. Studies such as Goode *et al*. (2021) show that in the period of 1998-2017 there was a climatologically significant decline in the global albedo (~0.5 W m^{-2}), which can be associated with the reduction of stratocumulus clouds over the ocean. With global warming, the convection over the ocean is increased and it leads to more cumulus clouds formation than stratocumulus. Cumulus provides subsidence and clean air areas among them, while stratocumulus covers huge areas. In the clear areas, radiation is able to reach the ocean surface increasing the warming and convection and decreasing the stratocumulus cover. Considering the water and energy surface budgets in South America, the reader can find some insights of the feedback mechanisms in Teodoro *et al*. (2021). Finally, from the view of each component of the climate system, we can also define climate as the state of the climate system as a whole, including a statistical description of its variations (IPCC, 2001).

NATURAL CLIMATE CHANGE AND VARIABILITY

During Earth's history, the surface and atmospheric energy balances were perturbed several times. Balance or budget means that what enters in a system leaves this system in the same magnitude. Imagine if Earth receives more solar energy that it releases to space, the result would be a huge warming of the planet. As the Sun is not the only driver of the climate alterations, the purpose of this section is to discuss some of the other drivers. However, it is important to begin with the definitions of climate variability and climate change. According to the glossary of the IPCC (2021):

> "*Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).*"

> "*Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use.*"

Note that in the definition of climate change there is a "change" in the climate while in climate variability there is a "variation" in the climate.

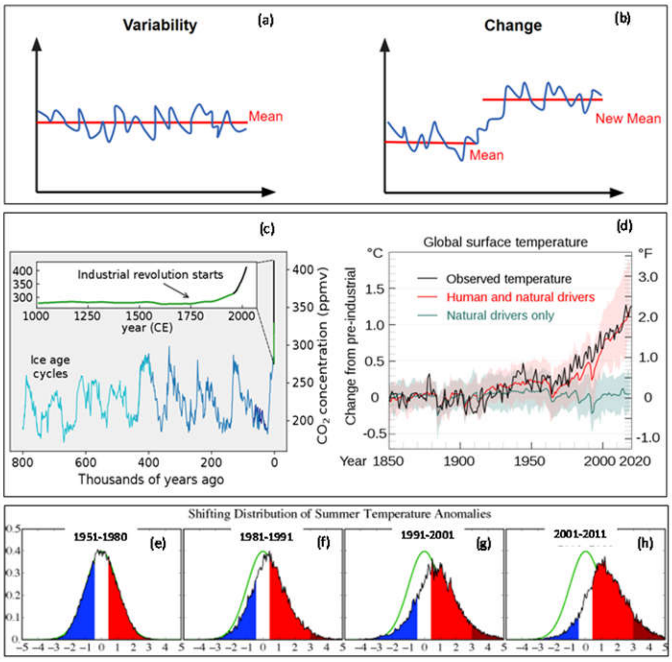


Figure 5 (a-b) Illustration of climate variability and climate change, respectively; (c) CO_2 concentrations over the last 800,000 years as measured from ice cores (blue/green) and directly (black) - https://www.wikiwand.com/en/Climate_change; (d) changes in global surface temperature relative to 1850-1900: anomalies of the observed data (black line), simulated using human and natural forcings (brown) and only natural factors (green) (SPM-7 IPCC, 2021); (e-h)frequency of occurrence (vertical axis) of local June-July-August temperature anomalies (relative to 1951-1980 mean) for Northern Hemisphere land in units of local standard deviation (horizontal axis). Normal distribution (green line) is used to define cold (blue), typical (white) and hot (red) seasons, each with probability 33.3% (source NASA/GISS; https://www.giss.nasa.gov/research/briefs/2012_ hansen_17/)

To clarify these definitions, one can think that climate change is a change in the mean value of the global temperature (such as a higher value along decades compared to a certain reference period; Figure 5b) whereas climate variability is a deviation (oscillation) in relation to the mean state of climate for short periods such as a dryer summer (one specific event) or the global cooling produced by a huge volcanic eruption for two years (Figure 5a). Figure 5c,d shows changes in the mean value of the CO_2 concentration and global surface temperature from 1900-year but, along the whole time series, there are embedded variabilities. Climate variability is largely understood in terms of recurring regional patterns (or "climate modes") related to natural internal dynamics of the ocean and atmosphere (Gupta and McNail, 2012). Figure 5e-h indicates that the increase in the mean of the surface temperature also implies changes in the extreme events. It occurs because the distribution of anomalies shifts to the right overtaking the normal distribution (green line) of the base period (1951-1980). Note that the right (left) tail of Figure 5h has an increase (decrease) of warm (cold) extreme events compared to normal distribution (green line). As climate change has occurred even in the absence of humans, there are natural drivers contributing to these changes. Figure 6 presents a synthesis of the natural drivers that can be external or internal to the climate system. External drivers modify the climate but are not modified by it while the internal drivers modify and are influenced by the climate (IPCC, 2001; Hartman, 2016). Internal drivers can lead to climate change when they are related to modifications in the thermohaline circulation, ice melting and water vapor increase in the atmosphere. But they are also greatly responsible for climate variability on different time scales (weakly, intraseasonal, seasonal, interannual, and decadal). This variability is associated with the teleconnection patterns.

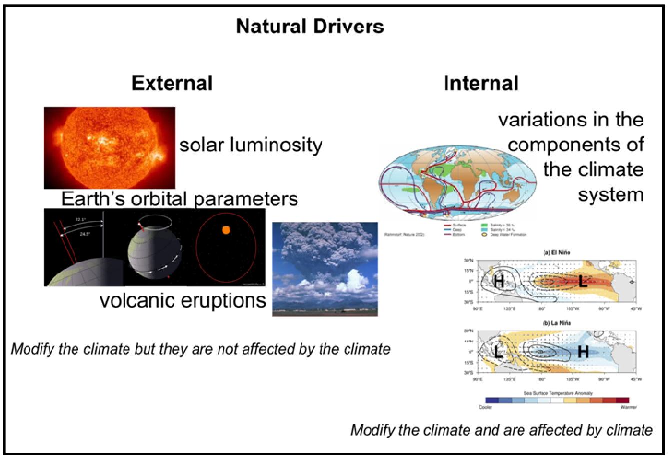


Figure 6 Natural drivers of climate change. Solar luminosity, Earth's orbital parameters (inclination axis of Earth's rotation, precession and orbital eccentricity) and volcanic eruptions are examples of external drivers while changes in the thermohaline circulation and El Niño-Southern Oscillation are examples of internal drivers

External Drivers

Solar Luminosity: If the Sun intensifies (weakens) its energy output it will warm (cool) the planet. However, the Sun's activity has been stable for a long time (Heller *et al.*, 2021), except for some cycles with little influence on the Earth's climate. As the Sun is a dynamic body its gases are constantly moving, which affect the magnetic fields characterizing the solar activity. Cycles of solar activity of ~ 11 years are characterized by dark areas on the surface of the Sun called sunspots. They are cooler areas caused by the magnetic field that keeps some of the heat within the Sun from reaching the surface. According to NASA (https://spaceplace.nasa.gov/solar-activity/en/), the magnetic field lines near sunspots often reorganize leading to a sudden explosion of energy, which is released into space. Sunspot activity (Figure 7a) can increase the solar energy reached at the top of the atmosphere by less than 1 W m^{-2}, which corresponds to a warm of <0.1°C (Hartmann, 2016). The absence of sunspots during the period 1645-1715 (called the Maunder Minimum) is roughly coincident with the period of the Little Ice Age in Europe (for more details visit https://www.climate.gov/news-features/climate-qa/couldnt-sun-be-cause-global-warming). The change of solar energy between the pre-industrial period and 2019-year is 0.06 W m^{-2}. It can be responsible for about 0.01 ^{o}C - around 1% - of the warming the planet has experienced over the industrial era.

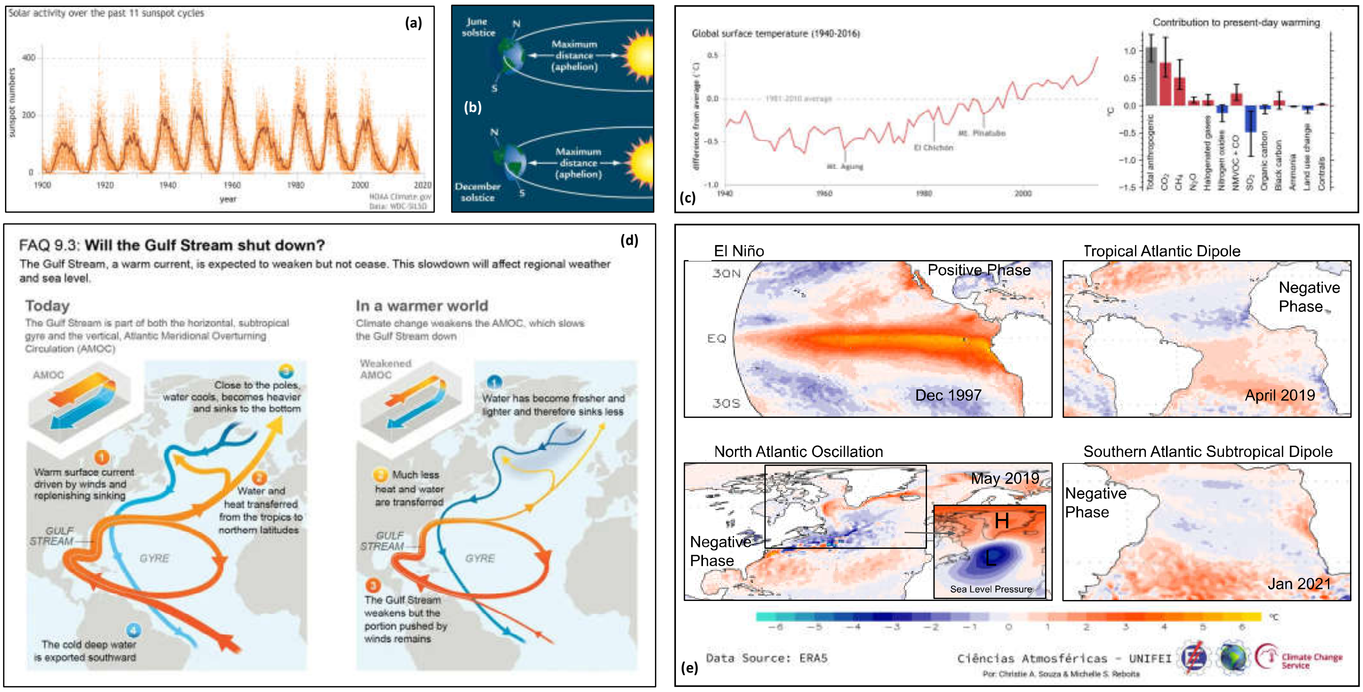


Figure 7 (a) Sunspot cycles (source: https://www.climate.gov/news-features/climate-qa/couldnt-sun-be-cause-global-warming); (b) precession (source: adapted from Ruddiman, 2008); (c)left: global air temperature anomalies (reference period 1981-2010) and three volcanic eruptions that caused cooling: Indonesia's Mt. Agung in 1963, Mexico's El Chichón in 1982, and the Philippines' Mt. Pinatubo in 1991. NOAA Climate.gov graph (source: https://www.accuweather.com/en/weather-news/how-massive-volcano-eruptions-can-alter-global-temperatures/350863); right: the contribution to present-day warming from emissions. Note the negative contribution of SO_2 to global warming. Adapted from IPCC AR6 WG1 (2021) Summary for Policymakers Figure 2c by Chris Smith (https://energypost.eu/how-multi-scenario-emulator-models-are-improving-climate-change-projections/); (d)illustration of the projected change in the thermohaline circulation over the Atlantic Basins (source: IPCC (2021) FAQ 9.3, Figure 1), and (e)examples of the sea surface temperature anomalies during four teleconnection patterns: El Niño, North Atlantic Ocean, Tropical Atlantic Dipole and Southern Atlantic Subtropical Dipole

Earth's Orbital Parameters: Orbital eccentricity, inclination axis of Earth's rotation and precession are called the orbital parameters of Milankovitch and operate on separate timescales (Figure 6). The orbital eccentricity is the shape of Earth's orbit as it moves around the Sun. This path changes from elliptical (oval-shaped) to nearly circular and it takes place every 100,000 years. Obliquityis the change in the axial tilt of the Earth. Currently, the inclination of the Earth's axis is 23.5^{o}, but this varies between 22.1^{o} to 24.5^{o} in periods about 41,000 years. Precession is a movement that changes where on the orbit the seasons occur. Precession does not affect the tilt of the axis, only where it is pointing; therefore, precession modifies the Earth position in the orbit where the seasons occur (Figure 7b). Precession cycle takes about 23,000 years. The combination of the orbital parameters of Milankovitch has been associated with the ice age's occurrence. These parameters practically do not change the energy quantity received on the planet but they modify the energy distribution over the latitudes. The energy reaching high latitudes of the Northern Hemisphere during the summer seems to explain the ice ages. Summer insolation is minimized when the eccentricity is extreme, and the Northern Hemisphere summer solstice occurs near the aphelion (when Earth is farthest from the Sun). But the inclination axis seems to have special importance. One can think that a higher inclination axis is favorable for the ice ages, but is the lowest inclination axis. Why? With higher obliquity, the boreal winters are more severe and the cold air cannot keep water vapor that is important for snow precipitation. Moreover, during boreal summer, the warming is more intense and melts the snow. Low obliquity implies less severe winters and summers and snow can accumulate during winter and does not melt in summer. Thus, the snow can accumulate over the years and massive ice sheets can develop. The key for the ice ages is the Northern Hemisphere since the ice sheets grow only over land, and most of Earth's land area has been concentrated in this hemisphere. However, Ruddiman (2006) highlights that CO_2 feedback also provides the extra boost that allows net ice growth along with the obliquity effect. It is related to the iron hypothesis (Martin, 1990). Decreasing Northern Hemisphere air temperature with the Milankovitch cycles, colder temperatures reduce the water expansion in oceans leading to a decrease in the sea level. So, more extension of continental area keeps exposed to the weathering and mineral dust rich in iron is transported from the continent to the ocean. This dust is a nutrient for the phytoplankton that develops/growths and, consequently, absorbs more quantity of CO_2 during the photosynthesis. As CO_2 is being removed from the atmosphere, it decreases the greenhouse effect leading to a colder climate (and in this situation the sea level becomes lower and more continental area is exposed leading to a feedback mechanism). Martin (1990) also estimated that the concentration of CO_2 in the atmosphere during the ice ages decreased from ~280 to 200 parts per million (ppm).

Volcanic Eruptions: About once every 20 years there is a huge volcanic eruption that throws out a great number of particles and gases (mainly SO_2). It, generally, causes a cooling on Earth since the Sun's energy is reflected again to space when reaching these particles (Figure 7c). Volcanoes can also cause warming when they release greenhouse gases into the atmosphere. Although the eruptions are a local phenomenon, they affect the globe and the particles reside in the atmosphere for about 2 years. Volcano eruptions are more a source of natural climate variability than climate change because they are not a long-duration phenomenon. Since the eruption of Mt Pinatubo in 1991, several smaller eruptions have caused changes in the radiative forcing of ~ –0.11W m^{-2} (chapter 08 - IPCC, 2013).

Internal Drivers

Thermohaline Circulation: In the oceans, there are superficial currents due to the action of the wind and deeper currents that are driven by differences in the water's density, which is controlled by temperature (thermo) and salinity (haline). So, deep currents are known as thermohaline circulation. This circulation begins in the polar regions. The complete description of the formation and displacement of the thermohaline current is provided by NASA tutorial (https://oceanservice.noaa.gov/education/tutorial_currents/ 05conveyor2.html). The thermohaline circulation also reaches the surface and transports warm waters. It can control the climate of some places such as Europe (Caesar *et al*., 2018) where without this current, it would be colder. Thornalley *et al*. (2018) observed that the thermohaline circulation has been weaker on average during the past ~150 years than during the previous ~1,500 years. Climate models also show a weakening of the ocean thermohaline circulation (Figure 7d), which leads to a reduction of the heat transport into high latitudes of the Northern Hemisphere, which can affect the climate of Europe and of other regions (IPCC 2013, 2021). What are the drivers of thermohaline circulation weakening?

The melting of the ice sheets and glaciers of Greenland and other Arctic areas are pouring large amounts of freshwater into nearby oceans, which, consequently, decreases the salinity and density of the local water. So, the thermohaline circulation towards the north sinks before reaching higher latitudes, decreasing its trajectory. Moreover, the rainfall increases in the North Atlantic projected by the climate models will also be a forcing to block the thermohaline circulation.

Teleconnection Patterns: Teleconnection refers to local anomalies in the atmosphere, which, in general, are caused by a heat source in the ocean (Trenberth *et al*., 1998), and that affects the climate of remote places. Then, teleconnections also refer to local anomalies in the ocean that disturb the climate system (IPCC, 2021 - Annex IV). We can also think about teleconnection as a perturbation in the climate system caused by its own components or in other words, they can cause climate variability in the absence of any significant change in the radiative forcing. Here, we present a brief description of some teleconnection patterns that have a great global impact. The most widely known and studied teleconnection pattern is the phenomenon El Niño-Southern Oscillation (ENSO). ENSO is an ocean-atmosphere coupled phenomenon that develops in the east and central portions of the tropical Pacific Ocean (Wang *et al*., 2017). When the sea surface temperature (SST) presents a positive (negative) anomaly in this ocean basin exceeding a threshold for a sequence of months, there is an El Niño (La Niña) phenomenon (Figure 7e). ENSO is a natural response of the climate system and is responsible, for example, for positive anomalies of precipitation over southeastern South America and deficit over portions of Amazonia and northeast Brazil (Reboita *et al*., 2021a). The positive SST anomalies during El Niño events can contribute to boosting global temperatures, increasing global warming in specific years (McPhaden *et al*., 2020). However, climate change can also impact ENSO. Cai *et al*. (2021) synthesized advances in observed and projected changes of multiple aspects of ENSO and mention that there is a projection of increase in the frequency of extreme El Niño events. Moreover, the ENSO projections have shown more intense and frequent El Niño events in the future climate with spatial pattern more similar to Modoki episodes than El Niño canonic (Freund *et al*., 2019). Over South America, the precipitation anomalies associated with El Niño episodes are projected to have the same spatial pattern from the historical climate but more intense (da Rocha *et al*., 2014; Gulizia and Pirrote, 2021).

The North Atlantic Oscillation (NAO) is the leading mode of mean sea level pressure variability over the North Atlantic (Hurrell, 1995; Hurrell *et al*., 2003), and although it can occur in all seasons, its amplitude is greater in winter when the atmosphere is more dynamically active. It is characterized by oscillations between Azores High (Subtropical North Atlantic) and Icelandic Low (Arctic) (Figure 7e). Thus, the difference in the mean sea level pressure of these two places gives the NAO index. NAO positive (negative) phase indicates below-normal (above-normal) pressure across the high latitudes of the North Atlantic and above-normal (below-normal) pressure over the central North Atlantic, the eastern United States and western Europe. Both NAO phases are associated with changes in the jet stream and storm track over the North Atlantic (more details in https://www.ncdc.noaa.gov/teleconnections/nao/). According to Trenberth (2020), the NAO positive phase is associated with enhanced westerly flow across the North Atlantic, which moves warm moist maritime air over much of Europe and far downstream, while stronger northerly winds over Greenland and northeastern Canada carry cold air southward and decrease land temperatures and SST over the northwest Atlantic. In climate change scenarios, NAO has been projected to increase its frequency in the positive phase. For instance, Fabiano *et al*. (2021) obtained in the Euro-Atlantic region, significant positive trends for the frequency and persistence of NAO positive phase for SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios (vide section “Climate Modeling and Projections for South America” for details about climate scenarios) with a concomitant decrease in the frequency of the Scandinavian blocking and Atlantic Ridge regimes. These authors also mention that the increase in the NAO positive phase is consistent with a reduced meridional variability in the upper-level jet.

The Tropical Atlantic Basin is dominated by the Tropical Atlantic Dipole, which involves variations of opposite signs in the sea level pressure and SST (Figure 7e) in both hemispheres (Hounsou-Gbo *et al*., 2015; Foltz *et al*., 2019; Zhang *et al*., 2021), leading to variations in the position and intensity of the Intertropical Convergence Zone (ITCZ). The positive phase of the Tropical Atlantic Dipole, in general, is defined by the presence of positive (negative) SST anomalies in the North (South) Tropical Atlantic Basin. However, several studies evaluate the impact of Atlantic Tropical Basin on precipitation focusing only in one sector (north or south) of the Tropical Atlantic Basin (Reboita *et al*., 2021a). Episodes of positive SST anomalies over the tropical southern Atlantic displaces the ITCZ southward contributing to positive anomalies of precipitation over the coast of Northeast Brazil (Hounsou-Gbo *et al*., 2015; Reboita *et al*., 2021a). Studies, such as Saravanan and Chang (2000) and Zhang *et al*. (2021), have been shown that the SST variability in the North Tropical Atlantic Basin can be modulate by ENSO episodes. Zhang *et al*. (2021) considered the seasonality, time-varying ENSO frequency, and greenhouse warming to demonstrate that the cross-correlation characteristics between North Tropical Atlantic Basin and ENSO. North Tropical Atlantic Basin SST warming lags the El Niño mature winter phase, peaking in the following spring, which is caused by the Walker Circulation changes during El Niño episodes and the consequent Pacific-North America teleconnection pattern. Until December 2021, we did not find studies showing the projections of the Tropical Atlantic Dipole. On the other hand, there are studies that indicate SST trends in the future scenarios. For instance, Alexander *et al*. (2018) showed a positive SST trend over all North Atlantic Basin from CMIP5 models over the period 1976-2099. If it is projected a positive SST trend in future scenarios over the North Atlantic Basin and El Niño episodes can also warm the North Tropical Atlantic Basin, and as El Niño is projected to be more frequent and intense, we suggest a possible preference for the positive phase of Tropical Atlantic Dipole in climate scenarios.

The South Atlantic Basin is the stage of the Southern Atlantic Subtropical Dipole (SASD, Venegas *et al*., 1996; Morioka *et al*., 2011). This teleconnection pattern is also known in the literature by the South Atlantic Ocean dipole (SAOD; Nnamchi *et al*., 2011) and Extratropical Dipole (Bombardi *et al*., 2014). Negative SASD events are characterized by negative SST anomalies over the Tropical Southern Atlantic (off the coast of the Central Equatorial Africa/West Africa) and positive ones over the extratropical South Atlantic (off the coast of southeast South America) (Figure 7e). The SASD presents variability on the intraseasonal, interannual, and even interdecadal scales. The impact of this dipole over South America has been analyzed by some authors (Bombardi *et al*., 2014; Santis *et al*., 2020, Reboita *et al*. 2021a) and one interesting characteristic is the strengthen (weaken) of the South Atlantic Subtropical Anticyclone during negative (positive) events of SASD (Reboita *et al*., 2021a). For the best knowledge of the authors, we did not find any reference about SASD and SAOD in future scenarios. The Southern Annular Mode (SAM) is the main mode of natural climate variability of the Southern Hemisphere extratropical circulation characterized by perturbations of opposing signs (for example geopotential height) around Antarctica and a zonal ring centered near 45° latitude (Thompson and Wallace, 2000). The Climate Prediction Center/National Environmental Prediction (CPC-NCEP) defines the SAM index by projecting the daily and monthly mean 700-hPa height anomalies onto the leading Empirical Orthogonal Function (EOF) mode. The positive phase of the SAM index is defined by the presence of negative anomalies of geopotential height around Antarctica and positive ones in the zonal band around 45°S. The majority of the effects of SAM could be explained by its annular form and the related changes in zonal winds. As summarized in Reboita *et al*. (2021a), SAM positive phase is associated with weakening of the subtropical jet, strengthening and poleward displacement of the circumpolar vortex and zonal (westerly) winds around Antarctica and a higher frequency of cyclones near Antarctica and the subtropical South Atlantic Ocean, and lower frequency near southern Argentina (45°S). In terms of precipitation anomalies over South America, the positive (negative) SAM phase is associated with deficits (excess) of precipitation over the southeastern part of this continent (Reboita *et al*., 2021a). In the last decades SAM shows a preference for a positive phase (Reboita *et al*., 2021a) and observational and modelling studies have attributed this trend to anthropogenic factors, such as, the combination of stratospheric ozone depletion and greenhouse gases (Barnes *et al*., 2019; Fogt and Marshall, 2020). For future climate, CMIP5 models indicate predominance of positive SAM phase (Gillet and Fyfe 2012; Zheng *et al*., 2013). Fogt and Marshall (2020), through a review of the literature, indicate that simulations where ozone recovery is weaker or not prescribed, the summer SAM remains in a positive polarity through the 21st century, but simulations that include ozone recovery, the 21st century summer SAM ranges from insignificantly negative to positive.

The monitoring of the teleconnection patterns is crucial for seasonal climate forecast. For this reason, Souza and Reboita (2021) developed an online tool for monitoring these patterns that is available at www.meteorologia.unifei.edu.br.

Anthropogenic Climate Change

Greenhouse Gases: *Sources and Lifetime in the Atmosphere*

Greenhouse gases concentration into the atmosphere has increased since the first industrial revolution that began in Britain, by the 1760s, and spread to the rest of the world. Higher greenhouse gases concentration intensifies the greenhouse effect leading to the warming of the Earth's surface and, consequently, the adjacent air layers, as a feedback process in the climate system. The main greenhouse gases are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbons (CFCs). These gases have natural and anthropogenic sources. H_2O is the most abundant natural greenhouse gas in the atmosphere and has its concentration increased as the Earth's atmosphere warms, leading to clouds and precipitation formation. But, the highest "villain" for increasing the greenhouse effect is CO_2, which has its concentration greatly increased by human activities (Figure 5c). Burning fossil fuel and land use change (for example deforestation) are the main anthropogenic sources of CO_2 while the respiration of living organisms and volcanic eruptions are the main natural sources. In 1850, CO_2 concentration was about 280 ppm, in August 2021 was registered 416 ppm, which indicates an increase higher than 48% in the concentration of this gas (data provided by https://climate.nasa.gov/vital-signs/carbon-dioxide/). The main anthropogenic sources of CH_4 are decomposition of wastes in landfills, agriculture, and rice cultivation; ruminant digestion; manure management associated with domestic livestock; biomass burning and the natural sources are wetlands. For N_2O, artificial fertilizers in cultivated soils, biomass burning, fossil fuel combustion, nitric acid production and biomass burning represent the main anthropogenic sources of this gas while the natural are related to biological sources in soils and water. Finally, the emissions of CFCs are totally produced by human activities through synthetic compounds with industrial origin used in a number of applications such as refrigeration. When greenhouse gases are injected into the atmosphere, they have long lifetimes, i.e.,the amounts released into the atmosphere today will remain in the atmosphere for up to two centuries depending on the gas. The lifetime (except CO_2) is defined as the ratio of the atmospheric content to the total rate of removal (Hatmann, 2016). The lifetime of CH_4 in the atmosphere is ~10 years, N_2O is ~150 years, CO_2 is from 50 to 200 years and CFCs range from 65 to 130 years.

Land Use Impact: Changes in land use are also responsible for a great part of anthropogenic climate change. In Brazil, one of the major sources of CO_2 into the atmosphere is deforestation. When the vegetation is removed and/or burned, carbon (C) is released into the atmosphere and mixes with the O_2 creating CO_2. When forests are exchanged by grass, for example, although the albedo is increased (dense forests have green cover that absorb energy), there are a lot of positive feedbacks that produce local warming. Let's understand it. Rainforest canopy helps to trap moisture, it leads to slow evaporation, providing a natural air-conditioning effect (Henson, 2011). But, if the forest is exchanged by another crop, less moisture will be stored by the vegetation and in the soil and runoff is also expected to increase, then the energy received from the Sun will be converted into sensible heat flux that increases the local temperature. Note that deforestation affects the energy and water balances. The IPCC Special Report on Climate Change and Land (Shukla *et al*., 2019) summarizes the land use impacts on climate and its impact on the land surface and other components of the climate system. According to Shukla *et al*. (2019), agriculture, forestry and other land use contribute to about 23% of anthropogenic emissions of CO_2, CH_4 and N_2O. Anthropogenic warming has resulted in an expansion of the dry climate areas and decrease of polar climates, and the expansion of the dry climate areas are associated with the Hadley cell poleward shift (Reboita *et al*., 2019). Regions of dry climates are more vulnerable to desertification. The Special Report (Shukla *et al*., 2019) also defines desertification as land degradation in drylands (arid, semi-arid, and dry sub-humid areas), resulting from human activities and climatic variations. Desertification causes loss of biodiversity and reduces agricultural productivity, such as in the semi-arid region of Northeast Brazil (Vendruscolo *et al*., 2021), contributing to poverty in several places of the world. Desertified areas are more vulnerable to higher intensity of sand storms and sand dune movements, which cause disruption and damage to transportation and solar and wind energy farms.

Indicators/Evidences of Climate Change: CO_2 concentration almost doubled since the first industrial revolution. It is an indicator of anthropogenic climate change. The longest record of direct measurements of CO_2 in the atmosphere is from an island in the middle of the Pacific Ocean far from the huge industrial countries such as the United States and China (sources of greenhouse gases). Since 1958 the measurements at Mauna Loa Observatory have indicated the increase of CO_2 concentration in the atmosphere (https://gml.noaa.gov/ccgg/trends/) and its trend agrees with that from surface air temperature anomalies (Figure 5d). Then, CO_2 and surface temperature anomalies are indicators that support the IPCC (2021) declaration: "It is unequivocal that human influence has warmed the atmosphere, ocean and land." Through measurements of different environmental variables, it is observed that there are many indicators and/or evidences of climate change. Although the number of indicators is huge, the main are: increase in the greenhouse gases, surface temperature, atmospheric water vapor, sea level, ocean acidification, extreme events (droughts, floods, heat waves, cold waves etc.), and decrease in glaciers, ocean and land ice(IPCC 2001, 2007, 2013, 2021). For South America, Reboita *et al*. (2021b) assessed the frequency and trends of temperature and precipitation extreme events through different climate indices used in the literature (see for example IPCC, 2021 Annex V) applied in the projections of Eta regional climate model. One example is the consecutive dry days (CDD), which are projected to increase their frequency from 2050-2080 in the central part of Brazil, compared to the reference period (1980-2005).

CLIMATE MODELING AND PROJECTIONS FOR SOUTH AMERICA

Models and Uncertainties: Climate change refers to a change in the mean state of the atmospheric variables and/or in terms of extreme events distribution (Figure 5 e-h). In statistical terms, climate extreme is a certain probability distribution of a specific event, for example, droughts. Extreme events can be classified as weather extremes (short duration such as an intense daily rain) or climate extremes (long duration such as cold waves, heat waves, droughts). From observations we know that our climate is changing. So, it is normal that one can ask how the climate will be in the future? To answer this question, climate scientists use numerical climate models. Models are one way to represent reality. Hence, climate models simulate the physical processes in the atmosphere giving us the data that represent atmospheric circulation, temperature, precipitation etc. Climate models consist of physical equations that govern the atmosphere dynamics and are numerically solved using computers. However, for each component of the climate system there is a different model and we can couple them to reproduce a great number of processes in the climate system; these coupling models have been called Earth System Models. Before applying the models to project the future, scientists do a robust statistical analysis of the model's performance in representing the historical climate, which is called model validation. If a model is able to simulate the main features of the atmospheric circulation, the mean state of the climate (average temperature and precipitation) and the frequency of extreme events it gives usconfidenceto apply them in the future projections (McFarlane, 2011; Zong-Ci *et al*., 2013; Rong *et al*., 2021). When the models are used to provide future information, they also include scenarios. Scenarios basically are assumptions of the life conditions in the future; the assumptions of a more or not sustainable world arepathways (the definition of scenarios and pathways are provided by the IPCC, 2021, glossary: ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Annex_VII.pdf). Scenarios, therefore, are one source of uncertainty of the climate projections.

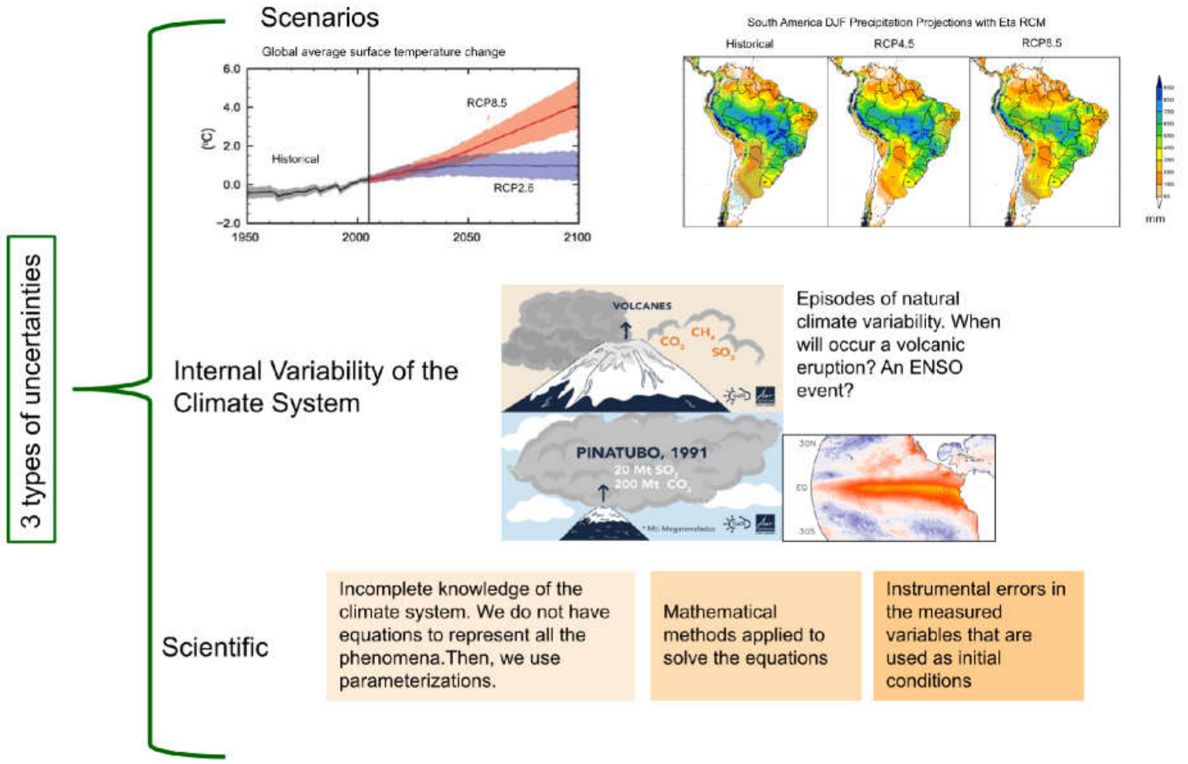


Figure 8. Three sources of uncertainties in climate projections: scenarios (top), internal variability (middle) and scientific uncertainties (bottom). South America maps are adapted from Reboita *et al*. (2021a) being the projections to 2050-2080

Basically, the models include three types of uncertainties (Hawkins and Sutton, 2009): scenario, internal variability and scientific (also known by model uncertainty) as shown in Figure 8. Scenarios are the different development pathways of the human being. The internal variability uncertainties are related to the natural climate variability, which is driven by internal and external factors to the climate system. One example is ENSO, which is a natural manifestation of the climate system, and the models do not know exactly the occurrence of them in the future, being a source of uncertainty. Another example is the occurrence of volcanic eruptions since models do not know when these events occur. Concerning the scientific uncertainties, they are related to the incomplete knowledge that we have about the climate system. There are no equations to describe all physical processes and several phenomena need to be parameterized (parameterization means that it is possible to account for the important effects of unresolved processes in terms of those that can be resolved; McFarlane 2011). Moreover, our observed data used as initial conditions in the model have spatial and temporal sampling limitations as well as measurement uncertainties associated with instrumental limitations (McFarlane, 2011). One way to reduce the uncertainties when we are analyzing climate projections is to work with the average of ensembles of long simulations (Sanderson and Knutti, 2012); each individual projection is called member. For instance, ensembles can be performed when different climate models assume the same climate scenario etc.

GCMs x RCMs: The models used to simulate climate can be global or regional. Global Climate Models (GCMs) simulate large scale features of the atmospheric circulation considering the whole atmosphere. For this reason, their horizontal resolution is limited to ~ 100 km. GCMs are driven only by initial conditions (observed atmospheric variables). If we are interested in a more precise representation of the local climate, Regional Climate Models (RCMs) are recommended. RCMs simulate limited areas of the planet. Their advantage compared to GCMs is that they have higher horizontal resolution (lower than 50 km) being able to represent aspects of topography and local circulations (land-sea breezes, valley-mountain breezes), for example. But RCMs also have a disadvantage: they need both initial and boundary conditions; this latter is provided by GCMs or reanalysis. The need for boundary conditions in RCMs is due to the fact that the small area prevents the waves from being displaced around the globe as in GCMs. A good review about the fundamental aspects of RCMs is available in Ambrizzi *et al*. (2019). Models can be also used to complement the knowledge that human beings are responsible for climate change. When models are integrated only with natural drivers of climate change, they do not reproduce the observed positive trends in the air temperature. But when the anthropogenic contribution is included in the simulations the tendency is obtained (Figure 5d).

South America Projections: Projections for South America have been performed mainly with two RCMs: Eta model and Regional Climate Model (RegCM). Considering the RCPs scenarios, both models agree with the dry conditions over the Amazon and wet ones over the La Plata basin in austral summer (Figure 8) and winter. On the other hand, the climate change signal over southeast Brazil has uncertainties since the Eta model projects dryer conditions during the austral summer (Reboita *et al*., 2021b) and RegCM indicates wet conditions (Llopart *et al*., 2021). Independent of model and scenario, warmer conditions are projected for South America. An online Atlas with climate indices projections for South America performed with Eta model is available at meteorologia.unifei.edu.br, option "Projetos".

IPCC: The climate information has been synthesized and spread to all global citizens by the International Panel on Climate Change (IPCC). IPCC was created in 1988 by the World Meteorological Organization (WMO) and the United Nations Environmental Program. Basically, the main objective of IPCC is to provide scientific information to the governments facilitating the development of climate policies (https://www.ipcc.ch/about/). IPCC has been supported by several research groups such as World Climate Research Program (WCRP) that manages the Coupled Model Intercomparison Project (CMIP; a review its history is provided by Touzé□Peiffer *et al*., 2020) and Coordinated Regional Climate Downscaling (CORDEX; Giorgi *et al*., 2021). Both are responsible for creating protocols for the simulations/projections execution. For the elaboration of the IPCC Sixth Assessment Report (AR6), CMIP (also in its sixth edition) provided the global climate projections performed with Shared Socioeconomic Pathways (SSPs; van Vuuren *et al*., 2017) scenarios while CORDEX provided the regional climate projections. RCMs were driven by the GCMs outputs from CMIP5 that used the Representative Concentration Pathway (RCPs; van Vuuren *et al*., 2011) scenarios. CORDEX did not use CMIP6 projections as initial and boundary conditions because RCMs consume a lot of time to finalize the projections and would not have enough time to wait for the CMIP6 projections to be nested in RCMs in order to provide information to IPCC-AR6. A historical review about the IPCC conferences and strategies is available in Beer (2018). A great challenge since the Paris Conference in 2015 is to limit global warming to below 2°C and pursue efforts to limit it to 1.5°C (Paris agreement). As shown in the previous sections, the average global air temperature has increased 1.1°C since the industrial revolution. If it continues increasing and overtakes 2°C, we reach the tipping points (Wang and Hausfather, 2020; Dietz *et al*., 2021), i.e., changes in some elements of the climate system that will be irreversible (one example is the savanization of the Amazon Forest). Then, the Paris agreement also aims to strengthen countries' ability to deal with the impacts of climate change and support them in their efforts to the strategies of adaptation and mitigation (more details are available at https://ec.europa.eu/clima/eu-action/international-action-climate-change/climate-negotiations/paris-agreement_pt).

CONCLUSION

This study summarized the knowledge needed to understand climate change and showed the human contribution to the observed and projected Earth's warming. We finalize this text with an important question: will we be able to control greenhouse gases emission? Recalling the Covid pandemic, we experienced and continue experiencing the global disarticulation to deal with the problem and associated with it, there is vaccine negationism. Climate change is facing the same problems. Recently, the 26th edition of the Climate Change Conference (COP26) from 31 October to 12 November 2021 in Glasgow showed the negligence of some countries to deal with the problem. Moreover, many people have been spreading "fake news" against science. How will be our near-middle and -far future?

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