

Chapter 2

How Climate Is Studied

The study of climate includes a large number of methods and techniques. Basically following the definition given previously, the most elementary method to classify climate is the collection of data on simple variables like temperature, rainfall, and so on. The requirements that climate should be based on several years averages already gives problems related mainly to the quality of the observations. How honestly could one compare a temperature data taken today with the same data taken one hundred years ago? Also some data were just not available in historical time. For example, think about the vertical profiles of temperature.

From this point of view, climate sciences already have some peculiar problems. They apparently utilize the same methods used in other physical sciences with quality degrading. As we go further back in time, another problem arises from the geographical distribution where the data are taken. Considering the technological progress in data gathering today, there are dense geographical networks that collect data, while in the past they were quite sparse. This may create some bias in evaluating the regional climates and their evolution.

Finally, an aspect is related to the distinction between weather and climate. Most of the climate data are actually derived from weather data which at the least in early times had different requirements. Today, a large part of climatic data is still derived from meteorological networks and the work to make them suitable for climate use is considerable.

In the following, we will give a summary of the most used methods to study climate, which remain entangled with the history of meteorology. At the end, a short paragraph is given on how climate is predicted and of course this aspect will be a common feature of all the following chapters.

2.1 Meteorology and Climate

At times we have mentioned the weather as the climatic “noise”. It is now time to mention some recent development of this concept. Even referring to the popular definition attributed to Mark Twain climate is a long-term average of the weather. This simple concept seems to be confirmed by the fact that both the numerical weather forecast and the climate predictions are made basically with the same General Circulation models (GCMs). In the first case, the model is run using initial conditions (like temperature, pressure, etc.) while in the second case, the boundary conditions are fixed (amount of greenhouse gases, solar radiation, etc.). In this case what results from the first “is what you get”, while in the second case “is what you expect”. We will resume this discussion in the next chapters.

This apparently is what the good sense dictates but it is not based on an objective analysis of the real data. Recently, Shaun Lovejoy of the McGill University has found (Lovejoy 2013), analyzing real data, that there are three regimes for the variables of the weather and climate. Between the weather, with a characteristic period of 10 days, and the climate, with periods longer than 30 years, there is the so-called macroweather. In very simple term if one draws the variations of temperature with a resolution of one hour, find that the maximum fluctuation is around 5° . If the same data are plotted with a resolution of 20 days, the maximum fluctuation is reduced to 1.5° and this value goes back to 5° for a resolution of 100 years. For example, with this resolution in a 100,000-year interval we can observe the ice age cycles with maximum fluctuations of 5° . Paradoxically on very long timescale, climate behaves as the weather (See Fig. 2.1). This discovery could change completely the perspective of climate predictions because (according to Lovejoy) GCMs do not predict the future climate but rather predict the macroweather. This is confirmed by the fact that the fluctuations predicted by the models are too small that may indicate that GCMs are missing some mechanism (connected probably to some slow process like the ocean circulation) that do not make them able to predict the climate but rather a long-term extension of the weather. This characteristic of the GCMs was already evident a few years ago in the analysis of satellite data performed by the group of Richard Goody at Harvard (Huang et al. 2002). This analysis did show some rigidity of the model with respect to the natural variability. This result could have some influence on the possibility to evaluate the quality of the models by comparing the spectra of their fluctuations with the spectra of the natural fluctuations and those produced by the presence of the radiative forcing due to the greenhouse gases.

In the previously mentioned paper by Palmer (2016) the author introduces what he calls the climatic Turing test. Originally, it was formulated to distinguish between human and artificial intelligence. The proposed test was to ask questions to the two entities and if the answers were same, there is no way to tell the difference. In the climatic case, the two entities are modeling and the data. If one compares the output of a high-resolution forecast model after 1-day integration, there is no way to distinguish between model and the real data while it is quite easy to tell the difference between a climate model prediction and the real data. This different

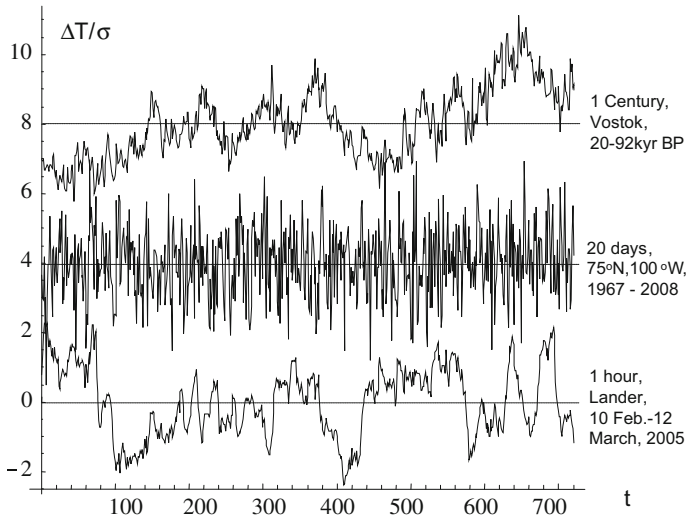


Fig. 2.1 Dynamics and types of scaling variability: a visual intercomparison displaying representative temperature series from weather, macroweather, and climate. To make the comparison as fair as possible, in each case, the sample is 720 points long and each series has its mean removed and is normalized by its standard deviation (4.49 K, 2.59 K, 1.39 K, respectively), the two upper series have been displaced in the vertical by four units for clarity. The resolutions are 1 h, 20 days, and 1 century, respectively, the data are from a weather station in Lander Wyoming, the twentieth-century reanalysis, and the Vostok Antarctic station, respectively. Note the similarity between the type of variability in the weather and climate regimes. Adapted from Lovejoy (2013)

behavior is another important difference between weather and climate that we will discuss often but for the moment we may take Tim Palmer comment:

I think the climate community worldwide does not give enough priority to developing a model which passes the climatic Turing test. We make do with our imperfect models, typically subtracting out the systematic errors against observations when estimating the impact of climate change. Journal referees recognize that this is the best we can do given the current generation of models, and so scientific careers can flourish without having to address the more fundamental question: Why is it so easy to tell the difference between model output and the real world?

Some years ago another possible interaction was proposed between meteorology and climate or between weather forecast and climate prediction. In order to improve the reliability of the latter, Palmer et al. (2008) proposed the so-called “seamless” prediction:

This is where the notion of seamless prediction can play a key role. It will be decades before climate- change projections can be fully verified. However, our basic premise, illustrated by the schematic in Fig. 2.1, is that there are fundamental physical processes in common to both seasonal forecast and climate change timescales. If essentially the same ensemble forecasting system can be validated probabilistically on timescales where validation data exist, that is, on daily, seasonal, and (to

some extent) decadal timescales, then we can modify the climate change probabilities objectively using probabilistic forecast scores on these shorter timescales. The magnitude of this calibration reflects the weakness in those links of the chain common to both seasonal forecasting and climate change timescales.

In practice it was proposed to calibrate the model for the long-term climate projections on the seasonal forecast which are now performed by several meteorological centers that sometimes also perform climate prediction. This would help to isolate possible weakness in the several modules that constitute a long-term prediction model. Recent attempt to utilize such technique has given encouraging results.

2.2 A Very Short History of Numerical Modeling

Weather forecast follows a historical path very similar to any other science especially physics. The second world war saw a great progress in the comprehension of the general circulation of the atmosphere with the major contributions coming from Jule Charney, Eric Eady, Hans Ertel, and Carl Rossby. The general problem corresponds to that of a rotating fluid like the Earth's atmosphere and its complexity is acknowledged especially for its mathematical aspects. Jule Charney to solve one of the central problems (the baroclinic instability) had to recur to some sophisticated mathematical function (Charney 1947).

The problem is that the time evolution of the variables which describe the system (like temperature, wind, humidity, etc.) is established through a number of nonlinear mathematical equations. This means that the response of the variables is not proportional to the causes that determine their changes. Or else the instantaneous change of one of the variables depends on a combination of the other (like a product). Charney to solve these equations utilized very sophisticated mathematical methods that were time-consuming because most of the time they required tabulated function. John von Neumann developed integration techniques that could be used on a computer machine (Smagorinsky 1983; Nebeker 1995; Dyson 2012). Toward the end of the 40s, the development of the first numerical computer coupled with these integration techniques brought the first numerical forecast in 1948 based on the theoretical concept of potential vorticity. Progresses are constant and the next big step comes in the 60s with the introduction of the weather satellites that fill the gap to have data on a global basis especially for those regions inaccessible to direct measurements.

In the same years, Edward Lorenz (1963) working on a set of simplified equations to study convection in fluid dynamics discovered that nonlinear systems behave in a very strange way. Notably, the prediction of the motions depends critically on the initial conditions. The solutions were so sensitive to the initial conditions that their precision would be crucial: it was the discovery of the deterministic chaos. Lorenz was a meteorologist who had passed all the stages of the trade, thanks to his genius; today, meteorology is a respectable science that has opened new horizons also to another realm of physics.

The consequences of the Lorenz discovery impact directly on the weather forecasts because the inescapable error in the initial conditions propagates rapidly in the course of the integration and after sometime (3–5 days), the error is so large that the forecast loses any meaning. This corresponds to affirm that the system loses memory of its initial conditions. The situation may be more complex than that because sometimes the precision of the measurement could be acceptable but the resolution of the model is too poor to accept that data. For example, the resolution of some satellite data today is of the order of 1 Km, but many of the forecast models and none of the climate models reach that resolution.

Meteorology is then a very respectable science because it is based on a continuous exchange between the observations (ground based and satellite data) and the numerical methods that have introduced new concepts in science like the assimilation techniques. This is a process that relaxes the solution toward the observed data.

This implies organization and economic efforts that put meteorology in the category of the big sciences. Think about the constant maintenance of the large technological apparatus (radars and remote sensing instruments). To the replacement of more and more sophisticated satellites, think about the huge amount of data produced that have to be processed. This effort requires an aggressive scientific community made by high priests who seat in the forecast centers and peones who are the interface with the community (i.e., weather men). This community has become an important power group that runs heavy international organisms (like the World Meteorological Organization, WMO) and has the tendency to occupy also the climate realm. This community is rather peculiar because it on one hand makes science (scientists are those who make science as Lewontin and Putnam affirm) while on the other has an unmatched applicative side. It is even different from medicine whose scientific basis must be found in other sciences like chemistry or biology. Meteorology has built his own scientific corner which is largely unrecognized. None of its great pioneers (we listed a few but many others could be added) has received the Nobel Prize (for those who care).

2.3 Earth's Climatic History: A Source of Data

At this point one would think that climate can be studied in the same way as meteorology, only on much longer timescales. A scientific study, however, requires the documentation about the relevant data, theories that explain the data, and the same theories (if correct) should reveal or predict new phenomena. Let us see if the study of climate responds to such requirements.

Starting from the data we know that the history of climate on Earth begins with the origin of the planet and that already force us to give up part of the story because the data of what could be the climate a few billions of years ago are rather confused. Any textbook you read on the past climate still give you the division based on different timescales from billions to million to hundreds of thousands years. Actually, we have only a very vague idea of what could be the climate from the origin until half billion

years ago and in any case data for that period cannot be used to test any theory. For example, during the last 25 years a new theory has emerged about snowball Earth. This theory argues (Hoffman and Schrag 2002) that for some still obscure reason, the Earth plunged into a state of being completely covered by ice. Geological data seem to confirm this episode that ends about 600 million years ago. However, the climatological data are of such poor quality that does not allow to test global climate models.

Another catastrophic episode of the Earth's climatic history relates to the dinosaur extinction about 65 million years ago. At the beginning of the 80s, a group of scientists that later became famous as TTAPS (Turco, Toon, Ackerman, Pollack and Sagan) proposed in a *Science* (Turco et al. 1983) paper that a global nuclear conflict could have triggered fires of such an extent to fill the atmosphere with soot that could have obscured the Sun causing what was called a “nuclear winter”. As a bad example of being carried away, the same TTAPS had proposed (Pollack et al. 1983) that a similar mechanism could have caused the extinction of the dinosaurs. In this case, the cause for the attenuation of light would have been the asteroid that hit the Earth according to the hypothesis formulated by Luis Alvarez some years before. The impact would have filled the atmosphere with dust. Actually, TTAPS had worked already on transient climatic changes due to the volcanic eruption (see for example Toon et al. 1982). In this case, they used very simple models that today any student may use as an exercise. However, considering the political climate of that time and the charisma of some of the TTAPS people, the noise was completely justified. The conclusions remained in a vague area good for *Discovery Channel*, but still that was not hard science.

As we approach more recent times the fog on the climatic data starts to thin out. Typical examples are the ice ages for which there are data that go beyond 4 million years ago. The ice ages are episodes of cooling of the Earth's climate that recurs with typical periods of 20.000, 40.000, and 100.000 years. These are the same periods that characterize the variations of some orbital parameters of the Earth, like the precession of the axis of rotation, its inclination, and the eccentricity of the orbit.

The change in eccentricity is such that the orbit around the Sun goes from a perfect circle to a very slight ellipse. In this way, the Sun–Earth distance changes from a constant value to a variable one. In the present epoch, the Earth reaches its minimum distance from the Sun around mid-winter (winter in the northern hemisphere) and its maximum distance in the summer. It is clear that a modulation of the distance introduces a modulation in amount of the instant radiation received by our planet. The rotational axis of the Earth is not perpendicular to the plane that contains the orbit of the Earth (ecliptic) and makes an angle of about 23.5° . This inclination is responsible for the seasons on our planet: when the axis points toward the Sun, we have summer in that hemisphere, and when it points away it is winter. The inclination is not constant but changes between 22.1 and 24.5° with a period of about 41.000 years. During the periods of maximum inclination, the difference in insolation between summer and winter are larger than during periods of low inclination.

Finally, the rotational axis not only “oscillates” but also “precesses”, that is, has a motion similar to a spinning top with a period of about 22.000 years. As a consequence, the position of the seasons around the Earth's orbit changes with time and this corresponds to the so-called precession of the equinoxes. The equinox is the day of the year when night and day have the same duration and this happens at the beginning of spring and fall, while Solstice is the day when the night has the shortest duration (summer solstice). In the present epoch, the winter Solstice (longest night of the year) in our hemisphere happens roughly on December 21, while the minimum distance from the Sun is reached on January 3. The precession of the equinoxes makes this distance to grow constantly so that the opposite situation (winter at the maximum distance) will be reached in about 11.000 years. At this point, it should be clear that the coupling between the precession of the equinoxes and the changes in the eccentricity is the one that produces the largest variations in the quantity of solar radiation reaching the Earth. Without doubt, the changes in the solar radiation related to the orbital parameters have an influence on the ice ages but many problems remain. One particularly important is the fact that while until 800.000 years ago the dominant period of the ice age was the same as the change of inclination (40.000 years); in most recent time, the dominant period is 100.000 years.

There are experimental facts about the ice ages that need explanations especially about the termination phase. As an example in the last ice age, the deglaciation phase was suddenly interrupted by a few episodes of climatic hiccups when the gradual warming was stopped and the climate went back to a glacial one. The most famous episode corresponds to the so-called Younger Dryas about 8000 years ago which had a global character. Further, there is the problem related to the atmospheric composition. At the onset of a glaciation, the decrease in temperature is accompanied by the decrease in the concentration of carbon dioxide and methane and by the increase in the atmospheric aerosols. All these phenomena do not have precise quantitative data but remain as “facts” that are explained in part or completely by ad hoc theories. Studies ran from purely phenomenological to rather sophisticated models and their results seem to point out an important role for the ocean. An excellent review on the ice ages can be found in Rapp (2010).

2.4 The Oceanic Circulation

The role of the oceans in the determination of the climate has received a wide attention by the scientific community. Two examples may give an idea how heated is the debate. One refers the Gulf stream and the other the so-called thermohaline circulation.

The Gulf stream is a surface current that moves from the tropical Atlantic ocean toward higher latitudes along the East coast of North America. For many years, people have assumed that such a current would explain the temperature difference observable between the East Coast regions of North America and the those of Northern Europe. The former are about 5 C colder than the latter. In 2002, a group of American scientists headed by David Battisti and Richard Seager (Seager et al. 2002) showed how the

effect of the oceanic currents was negligible with respect to the contribution of the atmospheric currents. A possible proof is the existence of a similar oceanic current in the Pacific known as Kuroshio Current that originates from the coasts of Japan and then moves toward northeast but misses the coasts of Canada and USA. On the other hand, winters in regions like Vancouver or Seattle have very mild winters that cannot be attributed to this oceanic current. The importance of the atmospheric currents is confirmed by the fact that the maximum heat transported by the ocean at about 20° North amounts to two thousands billion watts, while the atmospheric contribution is about six thousand billion watt at 40° North. This discovery made by Battisti and Seager has been almost completely ignored by those who sustain the role of the Gulf stream. Actually, it has a great importance for the climate debate because at the present it is thought that the mechanism for the ice ages depends on the intensity of the Gulf stream.

As a matter of fact, the Gulf stream is the observational part of more complex phenomena known as thermohaline circulation. Surface water in the Gulf of Mexico work as a giant pot where the evaporation is much larger than precipitation of fresh-water. As a consequence, these warm and salty water generate the Gulf stream that during their journey toward higher latitudes become more salty and cools and so are “heavy” with respect to the surrounding water. This causes the water to sink near the polar Arctic generating what it is known as North Atlantic Deep Water (NADW). According to the accepted theories, this deep current is part of global circulation that makes the deep water to emerge in different points of the world ocean like the Antarctic. The deep current is also known as Meridional Overturning Circulation (MOC) and has been popularized as the Great Oceanic Conveyor by its inventor Wallace Broecker. If the conveyor is “on” heat is transported from the tropical regions to the Arctic Circle and the planet is an interglacial (like today). If the conveyor is “off” the high latitude region in the Atlantic cool off and the planet is in an ice age. A way to turn off the conveyor is to dilute the high latitude salty water through the melting of the ice sheets. This theory is so popular that even Hollywood believes it as in the movie *The day after tomorrow*.

One of the main critics of this Hollywood theory is Carl Wunsch, a MIT oceanographer. Among the softest things he has written is that the thermohaline current can be observable only at the surface so that to utilize this concept for various theories is like pretend a meteorologist to use only a small region of the atmosphere for his forecasts. Actually, the Gulf stream is a consequence of what in oceanography theory is known as intensification of the western boundary current. In the Atlantic, the dominant wind system is such that at the tropics the wind forces the water toward the west (trade winds) while at middle latitudes, the water is forced toward the east (westerlies winds). In this way, some kind of vortex is generated in the Atlantic basin with a current adjacent to the North American Coast. For a number of reasons, this part of the current tends to be intensified, which is the origin of the Gulf stream. In order to exists the Gulf stream that needs the winds, a concept reaffirmed by Wunsch in a letter to *Nature* in 2004 (Wunsch 2004)

Sir—Your News story “Gulf stream probed for early warnings of system failure” (*Nature* 427, 769; 2004) discusses what the climate in the south of England would be

like “without the Gulf stream”. Sadly, this phrase has been seen far too often, usually in newspapers concerned with the unlikely possibility of a new ice age in Britain triggered by the loss of the Gulf stream. European readers should be reassured that the Gulf stream’s existence is a consequence of the large-scale wind system over the North Atlantic ocean, and of the nature of fluid motion on a rotating planet. The only way to produce an ocean circulation without a Gulf stream is either to turn off the wind system, or to stop the Earth’s rotation, or both. Real questions exist about conceivable changes in the ocean circulation and its climate consequences. However, such discussions are not helped by hyperbole and alarmism. The occurrence of a climate state without the Gulf stream any time soon—within tens of millions of years—has a probability of little more than zero.

Wunsch is a critic of the conveyor belt. He thinks that the complexity of the oceanic circulation can hardly be reduced to a one-dimensional model that even if it were true, the current would be extremely weak. In his own words (Wunsch 2010)

Broecker (1991, and many other papers), building on a sketch of Gordon (1986), reduced the discussion of the paleocean circulation to that of a one-dimensional ribbon that he called the “great global conveyor”. Its rendering in color cartoon form in Natural History magazine has captured the imagination of a generation of scientists and non-technical writers alike. It is a vivid example of the power of a great graphic, having been used in at least two Hollywood films, and has found its way into essentially every existing textbook on climate, including those at a very elementary level. It is thus now a “fact” of oceanography and climate. (Broecker 1991, himself originally referred to it as a “logo,” and it would be well to retain that label.)

This brings back the question whether the ice ages could be driven by a massive injection of freshwater at high latitude due for example to melting of the Arctic ice sheets. This was the theory about the Younger Dryas: The melting water gathers to a large interior basin (Lake Agassiz) whose flooding in the north Atlantic stops the conveyor, making the Northern hemisphere to return suddenly to an ice age. However, they discovered (Lowell et al. 2005) a difference of about 1000 years between the Agassiz floods and the beginning of the YD. In a more recent paper appeared in *Nature* (Murton et al. 2010) it is shown that even if that flood discharged it did toward the Arctic rather than in the North Atlantic. Here we have another side of the theories on the climatic change. Most of them are ad hoc theories based on the misuse of doubtful concepts (the conveyor).

The ocean then is fundamental in the determination of climate because it is an element of the system which has a capability of absorbing heat thirty times that of the atmosphere but its slowness does not seem to be compatible with the funding system. Wunsch says (Wunsch 2001):

Perhaps the greatest climate puzzle is whether one can find a way to study its “slow physics” (and chemistry and biology) within funding systems based on year to year budgets, high frequency elections, short tenure deadlines, and the general wish for scientific results in the short term. Understanding the ocean in climate is a surely a multi-decadal problem, at best.

There are then several problems to solve with the past climate and this is quite clear in the words of the inventor of the conveyor, Wallace Broecker (Broecker 2010). He

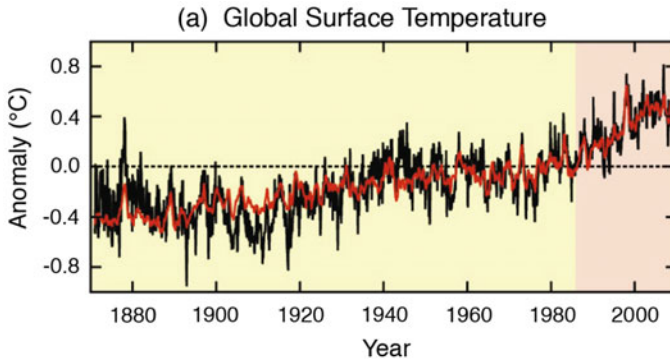


Fig. 2.2 The anomaly in the global average temperature in the last 140 years. The *pink background* indicated the year of the most recent increase in the forcing. The *red line* shows the average while the *black line* includes the fluctuations, Courtesy of IPCC report. Reprinted with permission by IPCC

remarks that his thinking was only marginally influenced by the simulations that have tried to reproduce the paleoclimate. He also observes that until models are unable to simulate the past it will be very hard to believe their predicting of the future.

A quite clear assertion considers that as we have seen the success in reproducing past changes are rather sparse and occasional (*ad hoc*). Besides the reconstruction of the past climate is still very qualitative and strictly related to the geological research.

2.5 Climatic Changes in Recent Times

Things should change as we approach our time as it is shown for example by the temperature data that now refer to the last 150 years Fig. 2.2. However, even this record is not completely reliable because the temperature standards used 150 years ago were not the same as today. We may affirm that reliable data could be assumed starting at the beginning of 1900. The curve whatever its origin shows a constant increase from 1900 to 1945 and then level off for about 30 years and they resume the increase until the end of last century. After this period there is a new apparent stop in the warming referred as *global warming hiatus* and has produced an avalanche of papers and discussions. The curve presents quite large fluctuations that may be useless to explain. During the past century, we had a number of catastrophic volcanic eruptions that may have influenced the climate. This is because the stratospheric aerosols that forms after the eruptions may reflect the solar radiation and cool the climate. Actually, the most important eruptions are Santa Maria (1902) in Guatemala, Agung (1963) in Indonesia, El Chichon (1983) in Mexico, and Pinatubo (1991) in the Philippines. The problem also in this case is that most of the data are missing except for the last two events. Actually, only the Pinatubo eruption has been properly

monitored from the ground and from the satellite. The most important tool to obtain data from the ground is the lidar. In the case of the Agung eruption, Giorgio Fiocco then at the MIT had just invented it and the quality of the data was not enough to prove any kind of theory. We will talk a little longer on this subject considering that of the most popular geoengineering scheme is based on the assumption that volcanic eruption cools the climate which may be not. It is enough to say that in 1978, Jim Hansen and coworkers (Hansen et al. 1978) could claim a complete understanding of the climatic effect of Agung eruption. Today, Canty et al. 2013 and Fujiwara et al. 2015 the volcanic signal is absent from a careful examination of the experimental or reanalysis data.

In spite of these uncertainties, many people have made a career out of them just to confirm that science is made by men. As we mentioned before, the temperature curve has generated ferocious discussions that have interested even the magistrate as in the famous episode of climate gate (see for example *Nature*, 468, 345, 2010). However, a very qualitative discussion attributes the constant temperature increase up to the second world war to the increase of the greenhouse gases. At the end of the war, the recovery of the industrial activity produces huge quantities of aerosols that may have compensated the warming effect of gases. This continues until the western countries develop legislation to contain the atmospheric pollution. These measures were so efficient that starting from the early 70s or 80s the ever increasing production of carbon dioxide determined a new increase in the temperature.

For the last 50 years, we have now a quite precise data known as reanalysis. This process reconstructs 3D meteorological maps than could be used as a test for climate models for some kind of 'hindcast'. It is quite strange that this has been attempted only partially.

2.6 How the Observations Are Made

The experimental methods used to obtain climate data are just an extension of those used in meteorology in the sense that the same database that covers an adequate period of time may be used in climate studies. The real problem arises with the data older than 50–60 years and the question is the intercomparison, that is, the evaluation of a data taken today with the older data even with a simple thermometer. It is not just the absolute value of the temperature but rather its precision. Do not forget that we are talking about changes of 0.5°C in 50 years and so changes of 10 thousandth degrees per year. It is true that the global data result from some kind of mean but the precision of measurement should be high.

We are talking about 50 years because this is the time interval covered by the reanalysis techniques. These have been developed at the end of the 70s and aim to make the measured quantities consistent with the model forecasts. In this way, data produced by models in some grid point are corrected by the observations that were not available at the time of the forecast. On the other hand, models may complete the data in those geographical regions where measurements were not taken. If we only

refer to the reanalysis of the European Centre for Medium Range Weather Forecast (ECMWF), the first project ERA (ECMWF Reanalysis) covers the period from 1978 to 1994 (ERA-15). The second project (ERA-40) covers the period 1957–2002 and ERA-Interim goes from 1989 to the present. This is an archive that gives the maximum reliability (see for example www.ecmwf.int/en/research/climate-reanalysis.) However, today people talk about period of time distant hundred of thousands years and pretend they have the same precision and reliability.

We can make the example of the ice ages. In this case, the breakthrough was the discovery of the Urey thermometer. At the beginning of the 40s, Harold Urey had found that the ratio of the most abundant oxygen isotopes (^{16}O and ^{18}O) was a function of the evaporation and condensation processes. This means that the continental ice sheets are enriched in the lighter isotope. The cycle is that of the evaporation at low latitude, when the clouds are enriched of the lighter isotope. The precipitation that forms the ice sheets is then enriched in the ^{16}O isotope. On the other hand, the ocean water are enriched in the heavier isotope. These water provide the oxygen in the calcium carbonate of some marine shells that go to constitute the oceanic sediments. A core drilling of the sediment may reveal an increase of ^{18}O that indicates an increase in the volume of the ice sheets. Cesare Emiliani (the brain drain has an ancient history) in the 50s was the first to show that from a core sample it was possible to obtain an estimate of the ice volume and then of the temperature. This technique has furnished, starting from the 80s a vast amount of data on the variations of the ice sheets volume in the last 3 million years. The spectral analysis of these data has permitted not only to isolate the harmonics at 20.000, 40.000, and 100.000 years (as seen before) but also minor changes before the onset of the ice ages or before their termination. The literature on this is immense (a good reference is Rapp 2010) but the conclusions we may draw on the evolution of the present climate are relatively poor. For example, the simultaneous changes of the carbon dioxide and the temperature are something like the old chicken and egg dilemma. There is no chance that such a data could be used to estimate the climate sensitivity because the environmental conditions were so much different from today. Besides while there is a quite precise estimation of the greenhouse gas concentration, the temperature changes may have a large relative error because their evaluation is rather indirect.

In any case, the isotope method and other similar techniques have contributed to a better knowledge of the Earth system involving aspects that go from geology to biology to the plant physiology. Everything goes in the general direction of a better understanding of the climate system but does not give direct clues on how it will be our near future.

2.7 Satellite Observations

The satellite observations related to the climate studies may date back to the end of the 60s when NASA orbited TIROS 3. This meteorological satellite operated a Michelson interferometer that is an instrument that measures the infrared radiation

coming from the Earth and could make very accurate spectra of this radiation. The name of the instrument was IRIS (Infrared Interferometer Spectrometer) and was invented by Rudolf Hanel of the NASA Goddard Space Flight Center. Since then IRIS (or similar instruments) has been employed in a number of sondes and satellites starting from the Mariner 9 that was able to characterize the Mars atmosphere in 1971 (Hanel et al. 1992). The infrared spectra of the Earth were characterized by the absorption of four gases, water vapor, carbon dioxide, ozone, and methane. The study of such absorption bands allows to obtain quantitative estimates of the interactions between the temperature changes at the surface and the feedback processes involving the different gases.

This technique received an important contribution from a research group at Harvard (Jim Anderson, Richard Goody, Stephen Leroy) that using the spectra of Nimbus 4 was able to show that the natural variability of the temperature was much larger than that predicted by the general circulation models. Based on this idea, but especially on the possibility of calibration in orbit, at the beginning of the new century, the proposal is made for a spaceborne instrument capable of absolute spectral measurements. The satellite that could carry the instrument initially is named Arrhenius in honor of Svante Arrhenius the Swedish chemist that was a pioneer of the greenhouse effect. The iteration that followed the project becomes CLARREO (Climate Absolute Radiance and Reflectivity Observatory) that is accepted by NASA but then is somewhat frozen in 2012. This proposed experiment could be the only one capable to measure quantitatively the evolution of the greenhouse effect on Earth, and so gives a definitive answer of what could be the anthropogenic contribution to the perturbation of the energy budget of the planet.

The other instrument on the satellites of the CLARREO project is a GPS receiver. We are now familiar with the GPS but most people (especially users) do not know that an important correction to the GPS signal is due to the atmospheric water vapor. This is because the refractive index of air depends on the quantity of water vapor that is present. This means that the GPS data can be utilized to obtain both the water vapor and the temperature of the atmosphere. These data are of such importance that is utilized to improve the weather forecast. Even today there are immense quantities of data referred to the temperature profiles of the Earth's atmosphere that covers the last twenty-five years. CLARREO utilizes this technique with the additional bonus of using calibrated data on international standards. The final product would be the evolution of the thermal structure of the atmosphere determined with a precision never reached before. These measurements can be carried out for a very long time, because they are calibrated and can be easily compared and could bring back the global warming in the realm of the physical problems. As we may have already mentioned that CLARREO was frozen by NASA, it has been canceled definitively by the Trump administration.

2.8 The Climate Through its Fluctuations

In 1975, a researcher at NCAR, Cecil Leith, published a paper on the *Journal of Atmospheric Science* (Leith 1975). In this work, Leith argued that the climate could be treated as a thermodynamic system (like a gas) where some quantities (like temperature) may exhibit spontaneous variations even in the absence of external forcing. In a gas, this is due to the fact that the molecules are subject to a random motion that is responsible for the fluctuations. Twenty-three years before Herbert Callen and Richard Green of the University of Pennsylvania had shown (Callen and Greene 1952) a thermodynamic system forced out of the equilibrium would return to the normal condition in a characteristic time that was the same as the decay time of the spontaneous fluctuations. Leith's idea was based on this hypothesis but was applied to the climate system. The climate system has an intrinsic "noise" that for example could be identified with the weather and may produce the observed fluctuations. In studying these fluctuations we may assume that their decay happens in a time which is the same as the decay time of the whole climate system. We can imagine a very simple climate system reduced to a forcing like the solar component and a damping like the infrared radiation. This could be assumed proportional to the temperature: if the solar radiation increases the temperature, more infrared radiation is emitted and the system goes back to equilibrium. The rate of decay depends on the thermal capacity of the system and the climate sensitivity and actually is the product of these two quantities. In a system with low climate sensitivity the return to the equilibrium is faster than in a system with high climate sensitivity.

In practice, the measure of the climate sensitivity is reduced to a measure of this decay time and this can be done by studying the so-called autocorrelation of a climate variable. From the autocorrelation, it is possible to determine the decay time and once the thermal capacity is known the climate sensitivity can be determined. A similar procedure has been used with the 150 years temperature records and the resulting climate sensitivity is just too low (Kirk-Davidoff 2009). From the discussions that followed, it seems to be clear that the idea may be correct while the data are not adequate. However, Leith's idea could also be applied to the autocorrelation of the emission spectra but again this requires a calibration of the measured spectra. A more sophisticated analysis shows that with a similar technique it is possible to compare the natural variability with that predicted by the models. We already mentioned this point and we will discuss it again later. Again the method outlined stresses the occasion missed with the CLARREO project.

2.9 How Climate Predictions Are Made

Before discussing this aspect, it may be useful to introduce even another definition of climate. Jonathan Rougier of the University of Bristol and his coworkers also challenge the idea that climate is "average weather" (Stephenson et al. 2012). They claim

that weather is a measurable aspect of our ambient atmosphere, notably temperature, precipitation, and wind speed. Climate as consequence is a subjective distribution for weather and it is not “average weather” because this would be just a summary of weather. On the other hand, climate is neither a “expected weather” because this is only one aspect of the distribution. What they really want to emphasize is that the statistical distribution also includes the extreme which is really the dangerous aspect of climate rather than the average. A possible consequence of this type of reasoning is that the climate for a generic year (or period of time) cannot simply be traced to the histogram of weather from the previous years. According to some basic statistical rule, this would require the years to be interchangeable while each climatic year is unique.

Based on these premises, Rougier has invented the concept of climate simulator (Rougier and Goldstein 2014). A climate simulator following the previous definition is a numerical device that turns climatic forcing into weather but in practice a climate simulator has as main element a climate model that could go from the extremely simple (like an energy balance model, EBM) to the most complicated (like a general circulation model, GCM). We will discuss again GCMs but what they do essentially is to integrate basic equations of fluid dynamics and thermodynamics to determine the atmospheric circulation and the associated effects. The integration is carried out with numerical methods on a three-dimensional grid. Models are run in time and utilize some forces which may include solar radiation, volcanic activity, and greenhouse gas concentration. Models cannot solve explicitly all the processes involved in the complex climatic system, so they utilize “parameterization” when the results of a process can be approximated by function of some variable already solved by the model like temperature for example. Some model utilizes something like 100 parameters and their uncertainties may result in a large spread in model prediction. A climate simulator is essentially a climate model fed with initial conditions, forcings, and a class of parameters. The output of the simulator will be mainly a function of those parameters with associated uncertainties. Rougier and Goldstein may then assume

Finally, our definition of climate seems to be consistent with current practice in climate modeling, as we describe in more detail in the following sections. A climate simulator is just that, a device for generating a family of distributions of weather. Insofar as the simulator is the outcome of many judgments, its distribution is subjective. Climate modelers do not accept one of the simulator’s climates as their own but make a subjective adjustment reflecting their judgment about the simulator limitations. So we find that the practice of climate modelers is inherently subjective, and that defining climate to be a subjective distribution of weather is reasonable not just from a foundational point of view but also from a naturalistic one.

Unfortunately, this approach up to now is not very popular and the climate predictions we will discuss in the book are based on the results of running a single GCM that may be with different parameterizations.

How Climate is Studied

A climate scientist and a humanist at the end of each chapter will discuss what we intended to say and what they have understood. The humanist in this case mostly tries to familiarize with some of the new concepts that the climate scientist insists should remain in the framework of the physical sciences.

H: It is interesting the distinction between meteorology and climate studies but it is not clear that they require very different approaches.

CS: Unfortunately, I think that one of the problems of the climate research is the assumption that climate could be studied with some by product of the methods used in meteorology. For example, the climate models derive directly from models used for the weather forecast. Today, this tendency is aggravated by the idea of the so-called “seamless prediction” that pretend to obtain climate predictions from a long-term integration of forecast models. The method is an invention by Tim Palmer

H: I understand that the differences are much deeper than that. According to Tim Palmer *However, probe below the surface and it can be seen that thinking about weather and climate forecasting as essential separate activities is not as scientifically meaningful as it might seem. Indeed, I would claim that trying to think about them as separate activities is actually hindering the development of climate science. Not least, weather prediction provides clear-cut metrics of model performance and it should therefore be used in the plethora of techniques needed to help develop a model which can pass the climate Turing test.* (see Palmer 2016).

CS: As a matter of fact, even if we remain in the modeling aspect, there is difference in the philosophy. The weather forecast models solve an initial value problem while the climate models solve a boundary conditions problem. This means that while the first starts from some initial observed conditions and parameters measured in some grid point, the second assigns general external conditions (like the amount of greenhouse gases) and arrive to a final state consistent with such boundary conditions. In recent times, some people is advocating the inialization of GCMs and we will discuss this in the coming chapters.

H: As I understand, there are also different ways to verify the results obtained in the two cases. I wonder if this is related to the climate Turing test.

CS: Well the Turing test for climate is a Tim Palmer invention to give scientific prestige to climate science. In this case, the models pass the test if you cannot distinguish between predicted and observed variables at the grid scale larger than the resolution of the model. Weather models pass easily this test. The weather forecast can be verified day by day as the data become available, while the climate predictions do not have such possibility. Only recently there have been proposals to test the climate predictions on a database that cover a few decades and are known as reanalysis.

H: The scientific character of meterology is confirmed by the fact that it has somewhat originated the chaotic theories.

CS: Not just meteorology because the discovery was the merit of Ed Lorenz, while he was studying a classical problem, that is, the convection in a fluid. However, Lorenz was a meteorologist and he applied some of the new concepts to study the predictability in meteorology. He showed that a small error in the initial conditions could propagate rapidly growing at the same time to the point that after a few days the prediction was completely unreliable. As shown later by Tim Palmer, this is not only the problem that limits the validity of the prediction but is also the limited resolution of the model that makes difficult to assimilate the data at high resolution provided for example by the satellite observations.

H: One of the critics is that while the meteorology has all the characteristics of a science, the same cannot be said for the climate that uses methods that show strong similarity with applied science. This means that its results are less trusted?

CS: We will talk about that in the following chapters but a careful examination of the paleoclimatic data gives a very bad impression on the scientific validity of the climate science. It is quite surprising that the scientific community treats these data as having a non-questionable quality. A few dissenters like Carl Wunsch affirm that for example the so-called paleo circulation of the ocean is poorly known and yet the ice ages and the theories that try to explain them are one of the most popular aspects in the scientific community. However, these works are very far from the rigor required by the physical sciences. The same thing is true for the most recent data that become reliable only in the last 50 years, while most of the debates on global warming assume that these data can be extended with the same validity to 150 years in the past. For example, if we consider the effects of the volcanic eruptions in historical times, the real hard data refer only to the last two great eruptions El Chichon and Pinatubo. Despite of this the literature is flooded with works based on nothing. In 1978, Jim Hansen and coworkers published a paper on *Science* claiming a 0.5°C drop in temperature after the eruption of Agung occurred 15 years earlier with data on the aerosol extrapolated from very indirect measurements, a questionable example of bad physics. Most recent papers based on the reanalysis data show very marginal effects.

H: It is not clear to me the origin of such scarcity of quality and quantity of data, especially when one thinks that the most recent data are obtained from satellite observations or very sophisticated methods.

CS: You must consider that climatic database are a direct consequence of the data produced by the meteorological networks. These data had important development starting from the second world war. The satellite data started to come in at the beginning of the 70s but these are mostly non-calibrated data and so they lack the quality required by the climatic data. Remember that we are talking about temperature changes of the order of 1 hundredth of degree per year and for such precision it is just out of question for satellite data. This is the reason why instruments have been proposed to produce calibrated data that can be compared with international standard especially for spaceborne observations. Such proposals have always found resistance from the

meteorological community. This because the limitation in the financial resources produces a very hard competition between the organisms that manage the meteorological data and the “scientific community”. This most likely is the one that succumb as recently happened for the CLARREO project. Another example of the imprecision in the data that have hindered the proliferation of theories deals with the method of the oxygen isotopes used to reconstruct the ice sheets’ volume. The precision of this method depends on the reconstruction of the depth of the cores that is a function of the sedimentation rate. However, this depends on the oceanic paleo circulation that, we have seen, is still in its infancy.

H: In the last part, it is suggested that the climate sensitivity could be estimated studying the fluctuations of the system. I understand that the climate system is made of fast component (like the atmosphere) and slow components (like the ocean). How this method distinguishes these two components

CS: There is no way to separate the two components. In practice, the study deals with the fluctuations as are integrated by the complexity of the climatic system. Unfortunately, it is a method that has given very contradictory results.

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