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What progress is climate science making to outline possible future scenarios? What degree of reliability do these offer? Models, causality and predictability in climate science.

Well, I, how can I say this, I have the usual extremely difficult task of speaking after the coffee break when everyone has had refreshments and is relaxed. However, in a quarter of an hour or twenty minutes I shall attempt to give you an idea of the main problems encountered when tackling this question. And I can't resist the temptation of starting with this transparency, and you can see that this is a place where young men are sprawled all over the place, there is not a book in sight, there are two pompous elderly gentlemen walking around; in fact it's the school of Athens and it's of interest to us because one of those elderly gentlemen, the one in the middle, is Aristotle (**see page 2**). Aristotle wrote the first book on meteorology ever written, the "De Meteorologica", where climatic changes are discussed at length. Why is it interesting? To explain that it is not that we have discovered climatic changes now; let us say that, if Aristotle was aware of these changes, probably the awareness of the fact that the climate as we know it changes, and changes often, was deep-rooted. The point is when one wants to move on from the vision let's say, of one's elderly aunt - "spring and autumn don't exist any more" - "it was warm at Easter and now it's cold" - when we want to move on to a scientific consideration, then the matter becomes a bit more complicated. Already the very definition of climate becomes a bit delicate. Above all, what is climate? Well, ladies and gentlemen, this is climate (**see page 2**). If it were a film, these would be the credits listing all the artists: you need the atmosphere, the oceans, mountains, ice, the biosphere, the sun. All this stuff is held together by water, water changes phase, it becomes liquid, solid, gaseous, whenever it changes it exchanges energy with the environment and creates a system, a highly complicated environment, where every small process, every small element counts, if one wants to reconstruct what's happening inside here one must bear in mind all these exchanges. Whenever water evaporates it exchanges energy and has to be counted, whenever it rains it takes on additional energy and has to be counted, so I could therefore spend the whole morning explaining to you that it's a complex matter, it's very, very complex, take the most complex thing you know, multiply it by five and you are underestimating the complexity of this system. You will have certainly have heard about butterflies which, when they flap their wings, they cause trouble everywhere, so, please, when you close doors be careful, don't slam the doors of machines too hard, otherwise the next cyclone will be put on your account. Is it really like this? Well, on the one hand, it clearly isn't, the system is a delicate one, but not as delicate as all that, otherwise it would truly represent a problem; on the other hand, it's a question of logic, because once things are so complicated, so delicate that, whatever counts, let's say, that any small forgotten effect produces an impact of global dimensions, how can we know this? How can we interpret it rationally? That is to say, a scientific consideration of such a complicated system, there is no doubt about it, science progresses by induction, science progresses by simplifying and finding the essentials, but if we cannot simplify the system, how can we present a scientific consideration? This is the big dilemma that modern climatology has had to face and so it's not surprising that the development of climatology, as a science, has been crippled by this problem, also because one of the consequences of this complication is that we cannot carry out experiments. Here you can see a famous experiment, the Michelson and Morley experiment (**see page 3**). The details don't count, this experiment changed the history of physics and the history of the world; the interesting thing for us is that the entire experimental apparatus is on that table. These two gentlemen, in a cellar, probably stopping to have their lunch or tea, changed the history of the world and the history of physics. Now, I would also like to conduct some experiments: for example the Alps are really annoying, I would like to eliminate the Alps and see whether the climate of the Po valley changes, Gibraltar - we were talking about the Mediterranean before - let's close it, let's build a dam at Gibraltar and see whether the Mediterranean really dries up at a rate of one metre per year, as our numbers tell us. These are crucial experiments, by making them we could get a clear answer to our scientific questions, and accidentally demonstrate whether Professor X or Professor Y are wrong. It's a pity that they don't let me carry them out, they don't give me the money and, above all, they don't give me the permission to perform these wonderful experiments, and so what do we do? Our only possibility is to have a parallel earth, which can be transformed, an earth where we can make all these changes and see what happens. We solved this problem by creating a virtual world where, by means of mathematical representations, we created a mock-up of the

relationships between the atmosphere, the oceans, water, all those components that I showed you before: this is what we call a numerical model. In this model we can perform the experiments we could not perform before, we can remove the Alps and, while we're at it, remove all the mountains of the world and, to be lavish, we can close Gibraltar, we can remove the Atlantic, we can change the shape of the continents, that is to say we can prove the theories, the assumptions we draw up on the functioning of the atmosphere and of the oceans and, in this respect, we are very fortunate because we did not have to do what our friends in theoretical physics had to do, we already had the equations at the end of the 19th century, the equations that govern the motion of the atmosphere and of the oceans already existed, and here they are (**see page 4**). The problem was to solve them; if anyone knows the solution perhaps they could contact me at the end of my presentation. We found a solution, which was to exchange the mathematical and analytical complexity of these equations with a huge number of elementary variations, it was the recognition of the fact that the symbols here are the indicators for a very large number of elementary mathematical variations which, at the price of an approximation, can be made in an explicit manner, giving rise to what we call discretization; in the place of derivatives, for the specialists, we place the differences, a huge number of differences, billions and billions of differences, all the calculations have to be made and at the end an approximate solution is obtained, but whose limits of validity can be strictly defined by mathematics. We owe this idea to a mathematician called Louis Richardson who, in 1921, carried out the first experiment on the numeric resolution of the atmosphere equation, on the grid that you can see (**see page 5**). He gathered a number of accountants together, practically filling a room, and made them do all those accounts by hand; it took them 24 hours to make a 24-hour forecast on the pressure in Berlin, that turned out to be completely wrong. Following this, Richardson was so depressed that the idea was abandoned for another 20 years until a group, connected with the Institute for Advanced Study at Princeton, basically inspired by von Neumann but revolving around the personalities of Jule Charney and Joseph Smagorinsky, solved some of the numerical and theoretical problems, for which Richardson's experiment had failed, and achieved the first numeric resolution of the equations of the atmosphere (**see page 6**). From that moment, the idea of being able to quantitatively describe the evolution of the atmosphere and the oceans has moved forward a great deal and so now we have models, permitting us to represent the entire climatic system. Why do we need these models? As the processes are all interconnected, as water has to be counted whenever it changes phase, the regions of the planet are interconnected, one with the other. It would be lovely to be able to say: "well, now I'm going to work on the climate of the Po valley so I can ignore everything that's happening elsewhere, I'm studying the Po valley, I'll fill the Po valley with instruments, I shall instrumentalize it to death and we'll see if we can, as they say, break the back of the climate problem. It's not like this, because what's happening in one place is caused by the variability of the climate in that place, and by the variability of remote climate. What you can see are the so-called teleconnections (**see page 7**), i.e. the fact that the temperature of the tropical Pacific determines the temperature of the Indian Ocean, but also the rainfall in Brazil, the monsoon rains in African Sahel and climatic anomalies in North America, and partly in Europe and the Atlantic. What does this mean? That the world is interconnected and the model has to be global, so we therefore have two problems - we have to take all and we cannot take regional shortcuts. The model has to take the whole world so, what you do is, you cover the earth with these numeric grids, where all the numeric calculations are made, and the atmosphere is sliced up, as are the oceans, etc. (**see page 7**). The processes represented are, practically speaking, all those existing in the atmosphere; as and when our knowledge increases, they are added and completed. We have a very long history of this development, starting from 1965 when the first model was designed, called the general circulation model. Present instruments are much more precise and more complete than in the past. For example, you can see that temperature is changed by both solar and terrestrial radiation and by cooling and heating processes, water vapour produces rain, water vapour influences temperature, etc., wind brings everything. Now, if you follow these arrows, every time you can close a closed path, you have identified a non-linear feedback, and so we can enjoy ourselves, let's say over the next hour and a half, counting how many non-linear feedbacks there are inside here, there are a great many, and it is from this that the sensitivity and complexity of the models derive (**see page 8**). You can do the same thing with the oceans, clearly things are different, here you have salinity and there are no clouds, etc, and in the end you can put everything together in what are the modern coupled models where both the oceans and the atmosphere evolve in a synchronized way. What are these for us? For us these models are like telescopes for astronomers or particle accelerators for high-energy physicists, they are the tools through which we investigate the reality of our planet. Whenever there is a new model, either because it has a higher resolution, that is to say a higher degree of detail, or because we have added processes that didn't exist before, basically we open a new physics, in the same way that LHC means discovering the Higgs bosons, we hope that the next model generation will be able to solve some of the processes, for example the non-hydrostatic processes which are extremely important so that, for us, this is a tool for

making experiments, increasing our understanding of the world, and generally attempting to understand what's happening. Italy has a special centre for doing this: it's called the Euro-Mediterranean Centre for Climatic Changes ([see page 9-10](#)). I don't want to advertise this, so I won't say any more. But one thing is interesting; it's clear that recently the climate change problem has become pervasive, as was the gradual realization that the change had a chain effect, let's say in all sectors of society. We, at the centre, have attempted to put everybody together, both people doing basic climate studies and those calculating impacts, both from the standpoint of agriculture, the energy market ecosystem, tourism and the economy. It's a delicate problem because all these experts speak different languages, but if they are not brought together at the outset, the risk is that the model makers will produce useless data for those who have to do the impacts and that the persons doing impact studies will have completely unrealistic expectations of what the models can do. This is an ambitious experiment, however we are carrying it forward with much enthusiasm. What is the main problem? This is what the Mediterranean looked like to the models recently used in the last report to IPCC ([see page 11](#)). You can see the detail of about 300 km, it's not bad, Italy's not there, for me this is rather an annoying, sentimental factor, and this is because, obviously, the more you increase the level of detail the higher the costs and the more you have to do, increasingly large calculators are needed. We conducted an experiment, our first simulations were carried out at this resolution ([page 12](#)), where you see, you can begin to see the Mediterranean and Italy, and we are now preparing a global model at a resolution of 60 km that will make it possible for us to properly see what is locally happening in the evolution of the film. Now, what does one do, after one has made all this effort, has set up these machines, has bought the calculators, has written the codes, has done the tests, has done all this stuff, what does one do? You could say, well, you can perform experiments; sure, we have performed experiments, we slowed down the earth for example, we tried to ascertain if the circulation of the atmosphere and the oceans changes when one slows down the earth. According to the fundamental principles of physics, one can also carry out different experiments, one can go to see what happens, for example, if you fill up the North Atlantic with freshwater. These are the experiments carried out. Clearly, at a certain point, when the fact emerged that we were changing the composition of the atmosphere, it was reasonable to ask what happens if one changes the composition of the atmosphere, especially in relation to those gases which represent the opacity of the atmosphere to terrestrial radiation, which are in primis, carbon dioxide, but not only that. You can see that it's a very simple mechanism, one increases carbon dioxide, the opacity of the atmosphere increases, terrestrial radiation becomes entrapped and to re-establish the equilibrium, the entire vertical structure of the temperature of the atmosphere changes, it's very simple, you don't need von Braun to do this ([see page 13](#)). However, it's obvious, that when one places this simple effect inside such a complicated mechanism, as I have just said, the results are not necessarily intuitive and therefore the fact that one uses a sophisticated climatic model to see what happens is justifiable. It's obvious that somebody has to tell me how much carbon dioxide, somebody has to make assumptions, they have to tell me, let's say, double or four times or triple the amount. That's what these socio-economic scenarios are, over the last few years they have been carried out with a highly significant effort by the international community, see above left ([see page 13](#)), there are these various curves, they correspond to various hypotheses on the history of CO₂ on a scale of 100 years, the green ones, I need hardly say, there's little CO₂, there's a lot on the dotted line, etc. But what is the interesting thing for us? It is that we can take these numbers, which represent concentrations of CO₂ year on year, put them in a model and see what the climate is balanced with these concentrations. Note that we do not make forecasts, the dates you see above are only indicative of the timescale, with respect to these scenarios, to which they refer. We do not forecast the temperature in Milan at eight o'clock in the afternoon on the fourth of April 2085, it's not possible to do that, what we are looking for is the climate balanced with this distribution of carbon dioxide or, rather, what the statistic is balanced with this distribution, and that's what we mean by scenario. There's a technology to make scenarios. This is what you do, either you completely double the concentration of carbon dioxide and then see what happens, an idealized experiment, or one starts with pre-industrial concentrations, then add concentrations observed in the twentieth century, and then use one of those scenarios to proceed. Now, this is the surface temperature of the earth simulated by the models, the blue line is the pre-industrial temperature, the black and red line stands for the concentrations of carbon dioxide observed in the twentieth century, and then there are the scenarios. Now, why does one use the surface temperature? The surface temperature is a mediate quantity, it mediates on everything, it's an indicator, a bit like when one looks, I don't know, at the stock exchange index to know whether things are going well or badly. However, this does not mean that your specific shares may do very badly even on a day when the stock exchange index flies high and vice versa; it's the same thing for surface temperature, there may be a situation where the temperature goes in a certain way, whereas there may be very different conditions locally, so this is a symbol, an indicator of what the status of the planet's climate is, but it is by no means the whole story ([see page 13](#)). Now you can see that in the twentieth

century the black curve, the observations, and the red curve, which is that of the model, are reasonably one on top of the other. It is in no way possible for us to simulate every inter-annual variation, this is because the climate is so disorderly; deterministic predictability, namely the fact of being able to follow the black line point by point, is absolutely, really impossible for questions of principle. It's the general trend that is of interest, and more sophisticated statistical analyses tell us that the model has the same habits as the real atmosphere, namely it produces winters within the variability observed in the twentieth century. For example it produces the right amount of rain for a monsoon, so this is an indication that our model is of the earth, and not of Mars, and this gives us a degree of reliability to follow the subsequent curves, corresponding to a decided increase in carbon dioxide, and see that they all move upwards. These are the results obtained in a systematic manner by practically all the models, also because, as I said, the mechanism is very, very simple, you don't need the help of a rocket scientist! Since the model gives us all this information, one can have fun looking at the details: for example, these are the differences in temperature indicated for the Mediterranean (**see page 14**). The model is global, but we are looking at a small window on the Mediterranean, and rapidly, to the bottom right you can see the difference in temperature in a scenario compared with the last century, and what you can see are familiar phenomena. You can see that, basically, summers are hotter, with a pattern very similar to the summer of 2003, and this, in itself, is already an interesting thing. Rainfall has similar effects, in essence it tends to diminish in the winter, it's top left, and this is quite interesting for us, because most of our rainfall comes in the winter and therefore any reduction in winter rainfall is a signal to be kept under control; all these, let's call them patterns, I'll show you, form part of changes at global level and are therefore robust, it's not local fluctuations that we can see. We can also simulate, for example, what happens in tropical cyclones, our model shows that by doubling carbon dioxide and quadrupling carbon dioxide, the number of tropical cyclones drops. This is because there is a specific feedback, so that, in the end, the result is counter intuitive, it doesn't necessarily mean that by increasing carbon dioxide, what can I say, disasters will definitely occur. On the basis of this, therefore, by doubling or quadrupling carbon dioxide, we find that the number of tropical cyclones, in effect, drops, and perhaps I'll explain why later (**see page 15**). So, how shall we conclude? Well, I think we should always be optimists; just because we are talking about this problem doesn't mean that, unexpectedly, so to say, the change in climate will hit us, nobody knew anything and will say oh! Sort of like a truck in the night with its headlights turned off; I also want to say, we should be concerned, it's not always that the taking of a definite stand is followed by a rational response, for example how many people in here smoke? Thank you, usually everybody says they don't, that's very kind of you. You see, if you ask somebody who smokes if they know what the consequences of their habit are, this person knows it all, all of it, all the tables, he knows how many years he will lose for each cigarette, the probability of getting this or the other type of cancer, he knows everything, but does he give up? No! So, we have this problem to solve, but I think we should solve it because, at times, challenging nature leads to terrible consequences and, if Tex says so, one should believe it (**see page 15**). Thank you.