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ANTHROPOCENE - NATURAL AND MAN-MADE ALTERATIONS OF THE EARTH

Climate models

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Abstract In this contribution, some of the issues related to the workings of climate models are discussed. The hierarchy of available models is mentioned, and examples are given of both the simplest process models and of state-of-the-art global climate models. The concepts of climate scenarios and climate predictability are discussed, and the methods for validating climate models are mentioned. Some of the many open questions in climate modelling are explored, focussing in particular on the issue of scale interaction: on the one hand, the need for downscaling the large-scale climate information for impact studies, using regional climate models and statistical/stochastic downscaling procedures; on the other hand, the need for up-scaling the small-scale dynamics associated with surface processes to quantify their effects on regional and global climate. The general theme of the parameterization of unresolved, sub-grid scale processes such as turbulent convection is also mentioned. The specific example of climate–biosphere interaction is considered in some detail, with specific attention to the issue of climate–vegetation interaction in arid and semi-arid regions and the role of vegetation in determining albedo and moisture fluxes. The need for a deeper understanding of the fundamentals of climate dynamics is finally advocated.

Keywords Climate dynamics · Climate models · Climate–biosphere interaction · Theory of climate

1 Climate science

Climate is a complex dynamical system, whose understanding requires the interplay of many different disciplines and approaches. In addition, climate varies on all spatial and temporal scales, from interannual variability to the lifetime of our planet, from one slope to another in small mountain valleys to differences at continental scales.

Like all sciences, the study of climate requires observations and data, and—today—we witness the availability of enormous quantities of high-resolution, precise and reliable data on our planet, provided by satellites and by a dense network of ground stations. The observational data sets are now so large that we have to cope with the serious problem of storing and efficiently accessing the information provided by the many measurement systems active on Earth, and of making these data available to scientists, decision-makers and final users. For this reason, international programmes such as GEO/GEOSS (the Global Earth Observation System of Systems, coordinated by the Group on Earth Observations which includes more than 90 governments and tens of international organizations, http://www.earthobservations.org/index.shtml) try to address the formidable task of making all data accessible to all interested users.

Data, however, are not the whole story. Data must be analysed and interpreted and they should provide the basis for conceptual understanding and for the development of theories. Parallel to the observational activities, climate science has developed a theoretical branch, which tries to build a coherent and rational view of "how climate works".

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As often happens in the scientific approach, this coherent view is expressed in terms of equations, using the language of Mathematics. Here, however, some problems appear. In fact, some parts of the climate system can be described by laws based on “first principles” (of Physics, Chemistry and fluid mechanics): for example, the dynamics of the atmosphere and the oceans, or radiative processes in the atmosphere. Other crucial components of climate, however, are necessarily described by empirical laws: we do not know the equations of a forest, but we do need to include forests (and vegetation in general) in our mathematical description of climate as they are a crucial player in many important processes.

In addition, even for the more “mechanical” components we cannot easily describe all climatic processes at once: it is not feasible to describe at the same time the motion of an entire ocean basin or of the planetary atmosphere, and take into account also the little turbulent swirls at the scale of a few centimetres. As a consequence, we need to simplify our description, and be content with describing just a part of the system: if we want to study turbulence, then we usually neglect the largest scales and model a cubic metre of air or water. If we want to describe planetary motions, then our resolution is necessarily coarse, and for now we cannot go beyond scales of a few kilometres. This introduces the well-known (and unresolved) problem of “parameterization”. That is, the attempt of describing the small-scale dynamics in terms of large-scale properties, assuming, one way or another, that the small scales are “slaved” to the larger scales and that uncertainties in the small-scale dynamics do not feed back (too wildly) on the larger-scale dynamics.

Given this situation, we need to develop strategies to simplify the problem of describing climate. One option, and the one adopted here, is to use reductionism, as commonly done in science. That is, we try to break the whole system into pieces, and describe them one by one.

A first approach is based on a splitting of the world into “spheres”: the atmosphere, the hydrosphere, the cryosphere, the biosphere, the lithosphere, the anthroposphere, and so on, as described in the upper panel of Fig. 1. Each sphere has its own equations, jargons, and parameterizations of unresolved processes, and it has its own models which become components (or modules) of the whole climate description. This way of splitting the known world comes from historical, disciplinary divisions: atmospheric scientists often have a different background (and sometimes work in different institutions) with respect to oceanographers. In turn, researchers working on vegetation come from a still different group, and so do scientists involved with the other spheres. By far, models of the atmospheric component have the longest history, based on the long-standing need for obtaining quantitative meteorological forecasts. Surface–atmosphere coupling and ocean models came a little later, and the other components were then added in a one-by-one fashion. The structure of the current global climate models reflects this division: there is an atmospheric module, an ocean module, a surface module, a vegetation module, often built independently of each other for somehow different purposes.

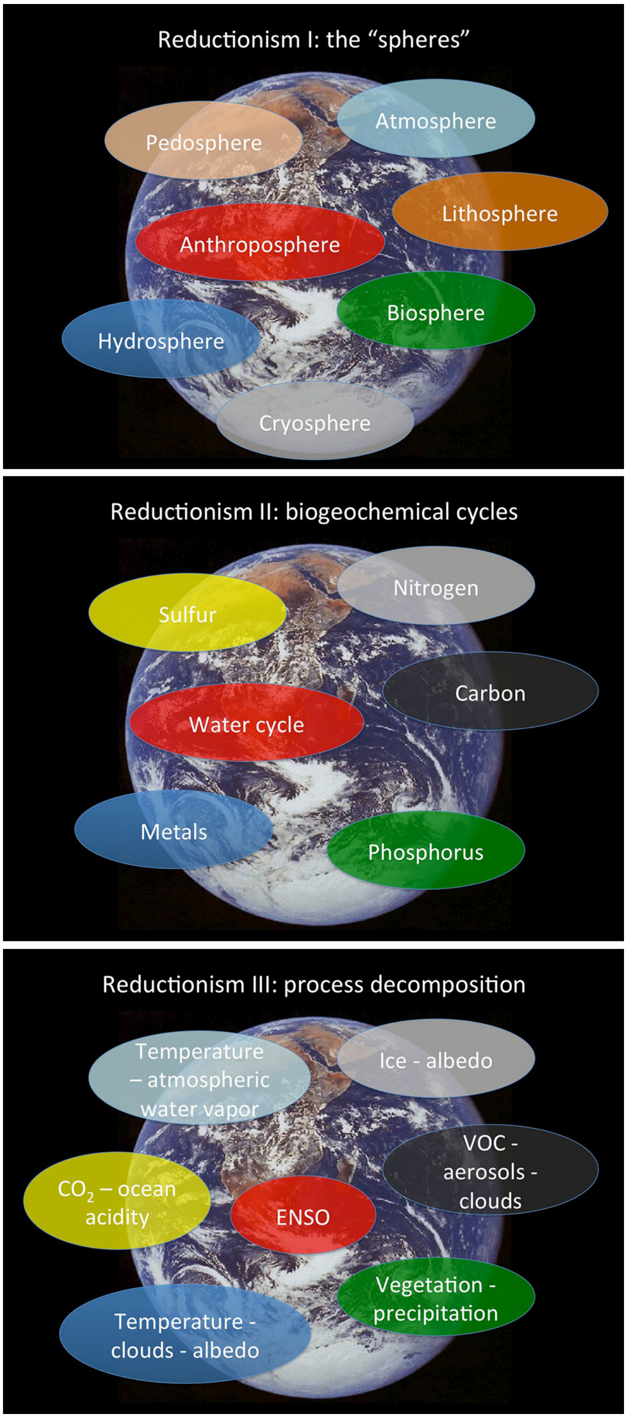

Fig. 1 Different reductionist approaches for disentangling the complexity of the climate system

Then, the game is to build a “coupler”, that is, a module that puts all these different pieces together and tries to harmonize resolution, time steps, and process description.

A second, more recent approach is based on looking at “cycles”, that is, to the transformations that different elements, or constituents, experience in their journey across the climate system, as described by the middle panel of Fig. 1. This way of seeing the world comes mainly from Chemistry and it is referred to as the study of biogeochemical cycles. Elements include carbon, nitrogen, phosphorus, and a special role is taken by water, which undergoes the climatically crucial processes associated with the hydrological cycle. Much has been learned about climate by considering such cycles, and some of them are now being incorporated, at least in a simplified way, into global climate models. Of these cycles, the many transformations of carbon and the hydrological cycle are at the heart of the climate machinery.

A third approach, which did not yet lead to a full climate modelling set, is based on the recognition that climate is composed by a large set of interconnected feedback loops, such as those relating temperature, albedo and ice, or temperature and clouds, or vegetation and precipitation. This is described in the lower panel of Fig. 1. Such feedback loops are due to the nonlinearity of climate processes and are often responsible for the presence of multiple equilibria and unpredictable behaviour.

In the following, we shall take a little journey across climate models. Given the extreme richness of this subject, only few specific issues, close to my personal interest and expertise, are discussed. The fabulous world of climate models encompasses many more topics, issues and questions which are ignored here. For example, more “holistic” approaches, not based on a division in components, can be adopted, as discussed by Pasini (2005). In approaches such as neural networks, it is the data analysis itself which indicates what links and correlations are important for describing the system, without imposing a priori, deterministic models. This approach resonates with the ideas developed in the “big data” world, where correlations, and not necessarily causal links, have been suggested to be the way to cope with the complexity of the system. However, in the following we shall focus on the more traditional, and perhaps old-fashioned, deterministic approach.

2 Climate modelling hierarchy

In developing climate models, we are faced with the need for compromise. On the one hand, we would like to include as many processes and mechanisms as possible, to provide a “realistic” description of the climate. On the other hand, as scientists we would like to understand what is happening, and for this purpose we need to simplify the problem and get something tractable.

Depending on the weight that we give to each one of these two often opposing needs, we end up with one type of model or another, as clearly discussed in the book by McGuffie and Henderson-Sellers (2005). To use an image developed at the Geophysical Fluid Dynamics summer program in Woods Hole (http://www.whoi.edu/page.do?pid=7937), we should find our place between the “bores”, who very carefully study almost irrelevant things, and the “slobs”, who cope with extremely important issues in a rather superficial way.

When we try to incorporate (all) the best of our knowledge, we turn to a global, or regional, climate model (GCMs: Global Climate Models, or RCMs: Regional Climate Models). Usually, these models incorporate the atmosphere, the ocean, the land surface, the cryosphere, the hydrological cycle on land, and, in the latest versions, the dynamics of vegetation, the carbon cycle and the chemistry of atmospheric aerosols. These models can be used for obtaining quantitative projections of future climates and are the standard tools which provide future scenarios for assessing the impacts of climate variability and change. Usually, these models require huge numerical resources, both in terms of computer time and storing space for the outputs, and require serious numerical skills to be built, updated, run and analysed.

At the other end of the spectrum, we find “process models”: simplified descriptions which deal with just one or a few elements of the climate system. These can be models which reduce the planet to a single zero-dimensional “box” or include a one-dimensional dependence on latitude (North et al. 1981), or try to provide a simplified description of the radiative-convective processes taking place in a vertical column of the atmosphere (Tyler and Catling 2012). These models usually do not provide quantitative predictions of the climate state but could be used to understand the role of different processes and the qualitative reaction of climate to specific perturbations.

In between the two, lies the world of the EMICs: “Earth System Models of Intermediate Complexity”, which incorporate many processes but include simplified parameterizations of the unresolved processes. In some sense, these are the GCMs of some years ago, which can now be used as numerical laboratories to explore climate dynamics and as learning tools for climate science. One interesting example in this class is the Planet Simulator, developed at the University of Hamburg (http://www.mi.uni-hamburg.de/index.php?id=216), which is complemented by a Graphic User Interface which allows students and scholars to “play with the planet” and see what happens when some important parameters (such as solar luminosity and CO_2 concentration) are varied. In the best of the worlds, these

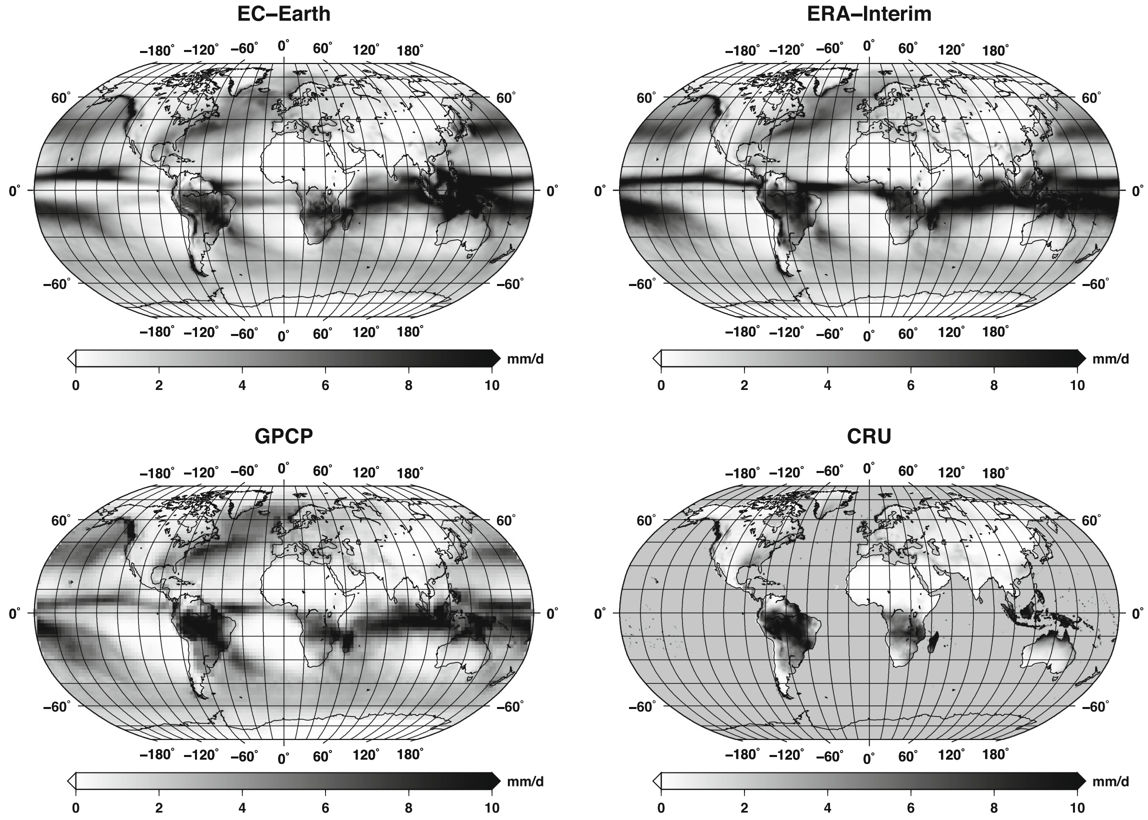

Fig. 2 Average precipitation in January, for the reference period 1980–2005, as produced by the EC-Earth Global Climate Model with spatial resolution of about 120 km at midlatitudes (*upper left*). The model output is compared with the ERA-Interim reanalysis (*upper right*) and with two different observational datasets, namely GPCP (*lower left*) and CRU (*lower right*). This comparison is extracted from the Master Thesis of Luca Filippi, University of Torino. Simulations and figure: courtesy of J. von Hardenberg and Elisa Palazzi. The model was run at CASPUR, now CINECA Rome (http://www.to.isac.cnr.it/ecearth/)

models are as understandable as the process models and provide semi-quantitative results. In the worst of the worlds, these models are as complicated as GCMs but provide only qualitative results as the simpler process models.

3 Global climate models

Global climate models are the most important, and perhaps only, instrument that the scientific community was able to develop to estimate the future climate evolution, and they include the results of several decades of passioned inquiries. Models are not perfect (in fact, all models are wrong, in one sense or another), as any scientist working with them knows very well. In this section, I discuss some of the questions which remain open, and which require new research and new efforts. But, to be clear, even though the tools we have are a little rough, they are the only ones we have.

There are, by now, several GCMs which are routinely adopted, and continuously ameliorated, for producing climate change scenarios to be used for impact studies (see for example the CMIP5 ensemble, http://cmip-pcmdi.llnl.gov/cmip5/). Most GCMs used to date use what are known as the "primitive equations" of Geophysical Fluid Dynamics, appropriate for describing the atmosphere and the ocean at large enough scales. The primitive equations can be obtained from the full three-dimensional Navier–Stokes equations by assuming that vertical accelerations are small compared to the acceleration induced by gravity on density perturbations, accepting the validity of the hydrostatic approximation also when the fluid is in motion (see for example Vallis 2006). In this way, vertical velocities are not determined by a prognostic equation (that is, time derivatives of the vertical velocity are neglected) and are diagnosed based on the continuity equation. Very roughly, this approximation can be used when the horizontal extent of the motion is (much) larger than the vertical extent. To illustrate the output of this type of model, we use the example of the EC-Earth model, developed by a European Consortium started by ECMWF in Reading and now including several European institutions from many different countries (http://ecearth.knmi.nl/). One of the advantages of the EC-Earth model is that it is open-access for European researchers, not only in terms of the outputs (which are available world-wide) but also in terms of source codes. Figure 2 reproduces a typical precipitation output from the version 2.3 of the EC-Earth model, currently run at CNR-ISAC, compared with different observational datasets.

After a GCM has been built, and numerical errors have been corrected, it is time to verify whether the model really works. To do so, the standard procedure is to verify whether the model is capable of reproducing the current climate (for example, the conditions encountered between 1850 and 2005, or those in a limited time span used as a reference period). In such procedure, some of the parameterizations of the GCM (or RCM) have to be tuned. Once a satisfactory representation of the current climate has been obtained, the model is then ready for producing climate projections. Validation often includes more subtle, and difficult, steps. For example, models can be used to reproduce climate in the distant past, under conditions which are quite different from the current ones: a success in this endeavour is an important sign of the model health, which can cope with different types of climate.

Once validated, climate models can be considered as a "virtual laboratory" for climate science. In the models, it is easy to change forcing factors and/or boundary conditions and explore the response of the system to "what if" questions, much as it is done in real laboratories when studying specific phenomena in fluid dynamics. Along these lines, climate models can be used for attribution studies, attempting at determining how climate would be if anthropic forcing were not present, or if natural variability (in volcanic eruptions, in solar forcing) were modified. Similarly, one can explore exotic situations where strong changes in solar emissivity, or in the concentration of greenhouse gases, or in the topography of the Earth are artificially introduced.

Unfortunately, however, climate models still include many uncertain and poorly known aspects which need to be addressed. The paper by Knutti (2008) provides general and very interesting considerations on the robustness of the results from climate models, and the recent findings by Stevens and Bony (2013) and Fyfe et al. (2013) indicate that there are several questions which should be addressed.

For example, the procedure called "parameterization" is, at the moment, a fatal curse of most climate (and weather/ocean) models. Current global climate models have a spatial resolution in the range 50–120 km, while most regional models have resolution of 10–50 km, and thus many processes take place at smaller scales. In addition, GCMs and most RCMs are hydrostatic, and cannot describe strong vertical motions. Atmospheric convection is a classic example of the limits of climate models: intense convective updrafts have horizontal size of a few km and cannot be properly resolved. Instead, they are parameterized: this means that the mean statistical properties (and effects) of small-scale, unresolved processes are described in terms of larger-scale atmospheric properties, assuming, in some way, that the mean behaviour of the fast, small-scale motions is determined by the slower large-scale circulations. Whether this is true, it remains to be seen.

In this framework, a delicate aspect of climate models is the treatment of cloud dynamics, which is linked, at least in part, with the problem of atmospheric convection. Clouds have both a heating effect, owing to the greenhouse effect of water vapour and droplets, and a cooling effect, owing to their white upper surface which reflects a large fraction of the incoming solar radiation. Which effect is dominant depends on the nature and height of the clouds, and on cloud microphysics. These processes, which take place at scales far smaller than those resolved by climate models, again must be parameterized and described in terms of larger-scale behaviour.

One of the main questions in parameterization is related to how uncertainty propagates across scales. If the effects of small-scale processes are confined at small scales (say, at scales smaller than the resolution of the model), then if we do not parameterize them correctly we do not do too much harm. Instead, if the unresolved processes introduce an uncertainty which affects ("propagates to") the larger scales, then ignoring the microworld hampers our ability to describe the macroworld. At present, we do not have a full and satisfactory theory of how the effects of small-scale "turbulence" propagate (if they do so) to the larger scales, and the whole universe of parameterization is, at best, an empirical and phenomenological construction.

4 Climate scenarios

Once a model is validated, it is run using, as forcing factors, possible or expected future conditions of the main drivers. This is the meaning of "scenario": with the model, we want to determine global climate conditions in case the emissions of CO_2, or methane, or aerosols take certain values. Similarly, we can explore the climate response to changes in land use, deforestation, or variability in the solar constant. For this reason, future projections are not "absolute", but refer to specific assumptions about the strength and characteristics of the forcing factors (Moss et al. 2010). This can be done at global level or, even more relevantly, at continental or regional scales.

Of course, things are not that simple. At present, there is no certainty about the social and economic developments of the coming decades, nor there is about the level of CO_2 emissions. To comply with the wide spectrum of possibilities, the various options have been combined into a large number of possible future scenarios. For each of these (which are based on different hypotheses on the level of globalization, land use, economic development, industrialization, greenhouse gas emissions, and so on) the climate model is run, providing the likely response of the climate system to such forcing factors. This is by no means the "true future", but rather a "what if" approach: an estimate, at the best of our knowledge, of what could be the climatic state for a given set of imposed conditions.

In this regard, one has to remember that climate is defined in statistical terms: in climate simulations we are not predicting the weather in Rome on the 9th of June 2058. Rather, with a climate model one wants to have an estimate of the statistical properties of the climatic state in the period 2040–2070 for a given set of forcing conditions: mean temperature, mean precipitation, intensity of the seasonal cycle, probability of extreme precipitation events and of summer heat waves, and so on. In this sense, even though the numerical models can be the same, weather predictions and climate projections are completely different efforts.

The difference between weather predictions and climate projections sometimes is a cause of confusion. A common objection to climate scenarios is based on the fact that "weather" is predictable only for a few days, so how do we pretend to predict climate decades ahead? This question confuses deterministic and statistical predictability, and it is worth a little more discussion using dynamical systems theory. In such framework, deterministic weather predictions correspond to predicting the position in phase space (the "state") of an extremely high-dimensional dynamical system (our mathematical representation of the atmosphere). Here, concepts such as the Lyapunov exponents are appropriate, and in a chaotic system such as the atmosphere the predictability time of the precise state of the system is limited: beyond the predictability time, the error on the state of the system is as large as the portion of phase space spanned by the system itself.

For climate, however, we want to estimate the statistical state of the system for a given set of external parameters. The closest analogue in dynamical systems would be to estimate the invariant measure (or some statistical measure) on the (chaotic) attractor. This problem is completely different from deterministic predictions, and the standard Lyapunov exponents do not play much role. This is not to say that the statistics are infinitely predictable, but simply that the standard meteorological predictability times are not relevant in this case. An extremely interesting, not necessarily well-posed, and quite difficult problem is to determine the predictability time of the statistical measures, as a function of the forcing factors and of the structure of the attractor itself (which may vary in time). At the moment, not much work has been devoted to this issue but some attempts are ongoing.

Given the statistical nature of climate projections, a single simulation is then insufficient. For this reason, "ensemble" approaches have been developed, where the same model is integrated in time for the same forcing functions, but starting from different initial conditions. After some time, the initial conditions are forgotten, but the phase-space dynamics of each model integration follows a different deterministic path. All together, the different runs provide information on the expected future conditions and on the natural variability associated with the complex dynamics of the climate system (that is, explore the climate attractor). Clearly, such an approach is extremely expensive from a numerical point of view. One way to solve this practical issue is the creation of open consortia, such as EC-Earth, where each participant runs a few members of the ensemble and in the end, the consortium can produce a large number of simulations for the same scenario and with the same model. Of course, one could also consider "multi-model" ensembles, where the different members are produced by different models. In this way, however, one mixes the "natural" climatic variability (as seen in a specific model), with the variability associated with the different parameterizations and numerical choices adopted by the different models.

Finally, an important difference between weather forecasts and climate scenarios is that weather prediction typically makes large use of "data assimilation", a set of procedures through which the model is continuously corrected by including, in proper and often rather complicated ways, the measured data (Kalnay 2003). In this procedure, the model trajectory in phase space is always "kept close" to the occurring weather conditions. For long-term climate projections this procedure is unfeasible, and the climate model is allowed to freely evolve under its own dynamics. The initial conditions, corresponding to the climatic state occurring today, are rapidly forgotten and the climatic system moves chaotically on the (possibly existing) climatic attractor. An interesting point of contact between short-term weather prediction and long-term climate projections is emerging at the scale of seasonal to multi-annual predictions, the realm of seamless predictions (Palmer et al. 2008), where data assimilation plays an important role for the initialization of the climate model on a state which is close enough to the measured one.

5 An issue of scale

One of the main problems in climate modelling is that the climate information provided by Global Climate Models is, at the moment, limited to resolutions between about 50 and

120 km. On the other hand, when studying the impact of climate change on ecosystems, the hydrological cycle, or runoff, we often need information with much more refined spatial resolution. If we think that an Alpine valley may be just a few kilometres wide, then it is clear that a resolution of 50 km (extremely high for the current GCMs) potentially misses not only the valley but almost the whole mountain chain. For this reason, addressing the problem of spatial resolution is one of the important issues for obtaining reliable estimates of climate change impacts on specific regions.

One option is to resort to "Regional Climate Models", RCMs (Giorgi 1990) which are based on much the same physics included in Global Climate Models, but have higher resolution (down to about 10–20 km) and describe only a limited (albeit pretty large) region of the globe (Europe, or Africa, or Central Asia, etc.). RCMs are "nested" into a GCM, in the sense that the Global Model drives the dynamics at the external boundaries of the domain described by the RCM. The RCM then produces its own climate inside the area, compatibly with the forcing imposed at the boundaries. The higher resolution allows for better describing regional-scale processes which could be overlooked in the global model.

There are, of course, some open questions. First, most RCMs do not feed back on the global model: they are passively driven by the GCM and do not contribute to ameliorating the GCM projections. On the other hand, if they did, one could question whether it is appropriate to have high resolution in just one part of the Earth and not elsewhere.

Second, the nesting process is not obvious in itself. How important is the way a RCM is nested? What is the trade-off between forcing the regional model to obey boundary conditions and allowing it to develop its own climate? Such issues are so relevant that some researchers think it would be better to push the resolution of GCMs to—say—30 km or so and directly use the outputs of the Global Model, which is—at least—consistently defined over the whole Earth. At present, all these different options are still alive and lively discussed in the scientific community.

However, even a spatial resolution of 20 km can be too coarse for many impact studies. To reach higher resolution, some alternatives are available, each of which has its own merits and drawbacks.

First, we can increase the resolution of regional climate models. Below 10–15 km, however, it is necessary to use non-hydrostatic descriptions because vertical accelerations in the atmosphere can become large, as happens for thunderstorms and for many intense mesoscale phenomena. There are now many non-hydrostatic models which are run for climatic purposes, sometimes at resolutions which can be as small as a few kilometres. Of course, these simulations require huge computing power and enormous data storage abilities.

Other approaches are based on the statistical or stochastic downscaling of the output of a (regional or global) climate model. Statistical downscaling seeks for a probabilistic relationship between large-scale atmospheric conditions (used as predictors) and a specific predictand, usually a small-scale feature of interest such as runoff in a given river basin (Maraun et al. 2010). Once such a relationship is found and it is shown to be statistically significant, then it is used with future climate scenarios: the foreseen large-scale properties of the future climate are used as predictors for the expected response of the variable of interest. This procedure has important merits, but it is based on the assumptions that (a) a significant statistical relationship between large-scale features and small-scale response does really exist, (b) such relationship is kept unchanged in the future, and (c) future climates are not visiting phase-space regions which were unexplored in current climate.

A variant of this approach is the so-called stochastic downscaling, which has been developed mainly for application to small-scale weather predictions and flood risk assessment (Rebora et al. 2006). This procedure is usually applied to precipitation, and it is based on generating small-scale precipitation fields with the correct statistical properties by extrapolating their larger-scale behaviour (for example, their power spectrum). In this case, what should be constant in the future is the relationship between the large-scale and the small-scale statistics of the same field (precipitation).

Whatever the approach, it is clear that the scale gap between climate projections and the needs of most impact studies is a major problem in current climate modelling, and it is one of the concerns of the scientific community working on estimating the response of surface properties (hydrology, terrestrial ecosystems, etc.) to climate variability.

6 Process models: the example of climate–biosphere interaction

The interactions between climate and biosphere are varied and extremely fascinating. About a century ago, Vladimir Vernadsky wrote the book "Biosphere", where he advocated the essential role of living organisms in determining the state of our planet (Vernadsky 1926). More recently, James Lovelock developed the "Gaia hypothesis", where the Earth is seen as a super-organism (or super-ecosystem) capable of regulating the climate through a series of feedback loops with homeostatic properties (Lovelock 1979). Although such visionary concepts are yet unproven in the large, they had the great merit of stimulating a deeper discussion of the role of living organisms in regulating climate, and have posed the basis for the study of biogeochemical cycles and the dynamics of the Earth System as a whole.

We all know that organisms are exposed to the vagaries of climate, and species distribution and phenology are responding to current climate change (Parmesan 2006). On the other hand, organisms can also change the physical environment, including climate.

Some organisms, called "ecosystem engineers" (Jones et al. 1997), can modify the environment they live in, and, in some cases, make it more suitable to their needs (but no teleology is implied). A classic example (besides mankind) is provided by beavers, which can change a valley floor into a lake and, as a consequence, change the whole local ecosystem, favouring aquatic species and making it less suitable to terrestrial species. Shrubs in arid ecosystems are another example, as they can modify the local soil humidity and nutrient distribution and create "islands of fertility" which are used by other plant species (Gilad et al. 2007).

As a result of habitat modification, the selective pressures on the organisms (of the species which are responsible for the modification and of the other species as well) are changed. In a sense, these organisms can build their own niche, and not simply try to adapt to pre-existing, fixed environmental conditions (Odling-Smee et al. 2003). This led to the so-called "niche construction theory", where the modification of the environment is another pathway through which offsprings can become favoured (in human societies, think of the bank account parents would like to provide their kids with).

From here to a Gaian view, the step is not that long. Perhaps, these local modifications can create a coherent network of regulating processes which make the Earth a complex, self-regulating system. Or maybe not: the different processes could indeed interact with each other destructively, with an "anti-Gaian" behaviour which could destabilize the climate and the biosphere itself, see for example the so-called "Medea hypothesis" discussed by Ward (2009).

For local processes to have a global (or at least regional) effect, it is necessary that mechanisms of upscale transfer of the induced changes are active. Usually, ecosystem instabilities take place at small scale, and it is not clear whether and how these local changes can propagate to larger scales (Rietkerk et al. 2011). This is a serious issue, which at the moment is not yet fully understood, and probably does not have a unique answer. Presumably, the presence of upscale transfer depends on the type of ecosystem and climatic conditions, and should be explored on a case-by-case basis.

At present, the effects of vegetation are included in many Global Climate Models, although often without a full dynamical response of vegetation (that is, without a full coupling between climate and vegetation). However, the equations of forests, savannas and grasslands are empirical, and it is not obvious how much the results depend on the parameters and on the description adopted in the models. Parallel to the "full-blown" approach to the problem, many simplified models have been developed to explore the individual processes by which vegetation can influence climate.

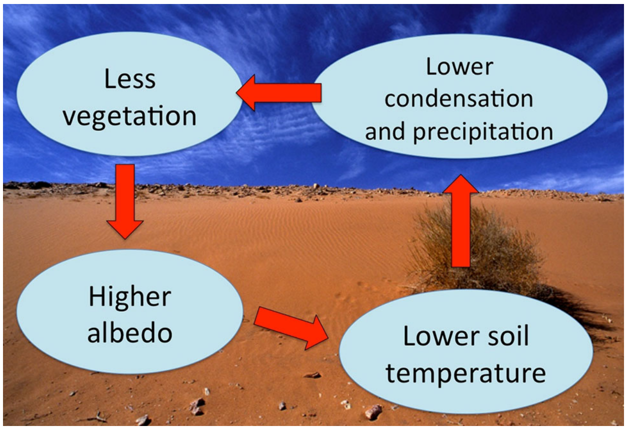

Fig. 3 An illustration of the Charney mechanism discussed in the text

A classic example is provided by the mechanism proposed by Charney (1975), see Fig. 3. Suppose you have a semi-arid region with some sparse vegetation. Now, think that some external factors reduce the vegetation cover. For many deserts, sand has higher albedo than plants, so the overall albedo of the region will increase and the solar radiation absorbed by the surface will correspondingly decrease. The soil will become colder, sensible and latent heat release to the atmosphere will be reduced, and the air column will become more stable. As a result, convective motions will be reduced (both locally and at synoptic scales, owing to reduced land–sea temperature contrast and a possible change of the summer monsoon). This implies that the area will receive less precipitation, with a further damage to the vegetation (which is water-limited in arid ecosystems). This is a classic positive feedback mechanism which can lead to multiple steady states, as indicated by simple energy balance-vegetation models (Brovkin et al. 1998) and by simplified climate models (Claussen 1998).

The change of albedo is not the only way vegetation can affect climate. In most continental areas, on average the water released by plant transpiration by far exceeds that associated with evaporation (Jasechko et al. 2013). Reducing the vegetation cover can thus significantly decrease the flux of moisture (and the corresponding latent heat flux) from the soil to the atmosphere, with important effects on the stability of the air column. Using a simplified box model, D'Andrea et al. (2006) found that the insurgence of continental droughts at midlatitudes (such as the heat wave of summer 2003 in France and northern Italy) is favoured by a dry soil anomaly at the beginning of summer, and Baudena et al. (2008) found that the absence of natural vegetation can increase the probability of summer droughts. With an extension of these box models, Cresto Aleina et al. (2013) addressed the problem of a hypothetical sandy planet where the presence of plants can trigger a hydrological cycle capable of sustaining the vegetation itself.

The interactions between climate and the living organisms are many and varied, and given the rather limited level of our understanding, all approaches from the simplest energy balance models to full GCMs should be pursued.

7 Fundamentals of climate

Much has been learned about the climate system in the last 30 years, and the best of this knowledge has been distilled into the construction of Global (and Regional) Climate Models. However, no model is perfect, and it would be a capital mistake to be content with the current state of description and think that everything will be solved using bigger, more powerful and faster computers, or by making the organization of climate science more similar to that of a big corporation.

Climate is a complex system and it includes many aspects which are still poorly known, such as the dynamics of scale interactions, a proper description of turbulence (and of convection), the co-evolution between climate and biosphere, and the same concept of climatic predictability. Basic research on these topics should continue, to provide better descriptions and—ultimately—better models for coping with society demands. Scientific activities in this field should certainly be coordinated and harmonized by large international programmes, but scientific progress ultimately will come from the passion and ingenuity of individual researchers.

For all these reasons, parallel to model development and scenario runs we need to focus also on the study of the fundamentals of climate, analysing available data, performing new measurements, using big models and little models, to explore the many, fascinating and crucial processes of the climate of our planet which are still waiting for a full understanding.

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