Digital technology and environmental research: Which direction?

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Abstract:
Research issues in ecology are all the more important because the various scenarios for an environmental transition call for a systemic approach with special attention to interfaces and coupling effects. The understanding derived from the digital sciences increasingly relies on model-building, simulations and the management of data and algorithms. The digital and environmental transitions raise questions for each other, and they share approaches. The issues and opportunities in the coming years are threefold. How to operate complex systems and models of them on several scales of time and space? How to handle the proliferation of data that, though hard to process and control, opens new prospects? And how to equip public policy with instruments for interventions?

At the turn of the 19th century, the Anglo-French fleet was battered by a severe storm during the Crimean War.[1] Urbain Le Verrier, director of the Paris Observatory, proposed to Emperor Napoleon III the formation of a meteorology office for predicting such catastrophes. In effect, had the storm been followed as it crossed the continent, it would have, according to Le Verrier, been possible to trigger a warning, since the telegraph could have transmitted the information.[2]

Let us now move up to forty years ago. Predicting atmospheric phenomena had advanced significantly. A pithy saying is that the quality of weather forecasts improves by a day every ten years. The trigger was now the progress made in digital simulations, itself spurred by continual advances in the capacities of big computers and digital hard- and software.

These two examples borrowed from the history of meteorology, though much too cursory, do illustrate the relation between research on the environment and the means for processing data. So, are we now facing a revolution, as is often said? Is this revolution a matter of the changes or of the degree of change?

We sometimes (and too hastily) place in the same category both current research on the environment and the responses to the issues raised by the environmental transition. This transition has several aspects — the climate, energy, the environment, food, etc. — that are distinct but not independent. They interact and call for a systemic approach. Although research on the environment cannot be reduced to the climate transition, the latter does point to a major, common characteristic of both: the need for a holistic approach for understanding, predicting, preparing, anticipating trends affecting the climate, biodiversity and the various parts of the Earth system; and, too, the need for environmentally friendly forms of technology for urban and rural planning, etc. All of this is happening during a crisis.

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[1] This article has been translated from French by Noal Mellott (Omaha Beach, France). The translation into English has, with the editor's approval, completed a few references.
[2] For a historical account, see Fabien LOCHER (2008), *Le Savant et la tempête. Étudier l'atmosphère et prévoir le temps au XIX^{e} siècle* (Paris: Presses Universitaires de Rennes, 2008).

During our anthropocene era,[3] human actions are deeply impacting the environment, with the risk of upsetting equilibria and causing: massive extinctions of plant and animal species, a radical alteration of the climate if global warming amounts to more than 2°C, the extreme vulnerability of societies faced with anthropogenic risks, etc.

To study these changes, research on the environment must encompass and compare different phenomena, detect their interactions, control interfaces, and reckon with a wide range of scales of time and space (from the planetary to the local). This requires diversifying our points of observation and developing as never before our capacity for building models for the purpose of understanding, predicting and acting.[4] In addition, the environmental sciences must also understand stakeholders' behaviors and profit from studies about them. They cannot rely on a "simple", physical or biological, view alone. The viewpoint adopted must encompass the variety of relations to life and the environment. As an illustration, the widely varying forms of relations to the soil or land, as studied by anthropologists,[5] are evidence that there is no single model of the relations between the human groups dwelling on our planet.

All in all, research on the environment has to give meaning to several phenomena with retroactive mechanisms that, at the planetary or regional scales, test the limits of our capacity for understanding and processing data.

In turn, what are the major characteristics of the digital sciences and digital technology? By "digital", we are referring to the principal disciplines (computer science, robotics, automatic control engineering, the processing of signals and images, telecommunications and electronics) and also to the relations with mathematics and model-building. Without claiming to present in detail the digital transition, we would like to point to a few trends of relevance for this article. In the past fifteen years, digital technology has undergone an acceleration in parallel to: an ever growing mass of data (along with the means for collecting and processing them), uninterrupted progress in electronic devices and machines, and regular advances in algorithms and all aspects of model-building, not to mention machine learning (all of this lumped under the simplified label of "artificial intelligence").[6] The comparison of the environmental and digital transitions is telling: the needs of research programs on the environment are reflected in the new opportunities arising from the advances made in digital technology. This leads to questions about scientific practices, as we shall see in matters related to defining and controlling data flows.

To better understand current practices, let us take a look at a few fields of interaction. These remarks are drawn freely from a report by Allistène and AllEnvi, two French research organizations devoted to, respectively, digital technology and the environment.[7]

The most obvious starting point is to understand and analyze the environment in its complexity and build models of it. In recent years, the digital and environmental disciplines have been interacting in the effort to understand the processes (human, biological, physical chemical…) under way at various scales of space and time. To understand current trends, we must combine models from our planet's various spheres (geosphere, hydrosphere, atmosphere, biosphere) so as to obtain a better representation of the processes involved. As we know, ocean-atmosphere interactions and the representation of them, like the interactions between the atmosphere and continental biosphere, are keys to making progress in weather forecasts and climate predictions.

This work requires digital tools (deterministic or probabilistic) and the ever more complex, demanding infrastructure for using them. As in the meteorological example mentioned at the start of this article, digital simulation is a core technique, whether for describing, representing or simply imagining scenarios — trends to which we must react or about which we must think in order to

[3] "A global perspective on the anthropocene", *Science*, 334(6052), pp. 7 & 34-35, October 2011.
[4] *Cf.* http://www.allenvi.fr/actualites/2017/scenenvi-futurs-pour-la-planete.
[5] Philippe DESCOLA, *Les Usages de la terre. Cosmopolitiques de la territorialité*, lecture at Collège de France in Paris, 2015-2016.
[6] For a fuller account, see: Alliance Nationale des Sciences et Technologies du Numérique (Allistène), *Presentation de l'Alliance* (Paris, 2011) available at https://www.allistene.fr/files/2011/01/ALLISTENE_Brochure-presentation.pdf.
[7] This 2015 report by Frédérick GARCIA (INRA) and Jérôme MARS (GIPSAlab, Grenoble-INP) focuses on interactions between the two fields.

describe their possible ramifications (whether to head them off or, on the contrary, hasten their coming). This holds in several fields: water (oceanography, hydrology), the atmosphere (meteorology, climate, pollution), agricultural ecosystems (biodiversity, farming), society (cities, transportation), etc. Research would take a big step forward by coupling models using different scales. The necessity of taking into account human behaviors introduces an additional degree of complexity, owing to feedback loops and, too, the difficulty in coupling models.

To control uncertainty, contemporary approaches to model-building use the tools for data assimilation (*i.e.*, preparing them for adaption as best possible to the model using them) and set-theoretic techniques (repeating a simulation with fluctuations in the initial state). Understanding the phenomena under study relies on building models and making simulations of complex systems. This implies designing more efficient algorithms. All this fosters developments both in environmental research, as it seeks a more integrated and finer understanding of processes, and in digital technology (in matters of computational intensity).

Another major issue has to do with big data and their processing. Progress in ecology is so closely linked to observations and to our increasing stock of knowledge on ecosystems that we might forget the quite clear risk of the data overwhelming us.

The expansion of observation systems (We need but think of the data from satellites, which are changing our vision of the planet) and the profusion of experimental data have radically changed our approach to ecology. To handle this continent of information, data-mining techniques must be developed; and this, once again, entails recourse to digital technology. At the international level, GEO/GEOSS is an intergovernmental initiative for developing a global Earth monitoring system based on national or academic systems. These observations are relayed over an e-infrastructure devoted to transmitting data and building a model of the Earth system. This program is molding environmental research.

It is not just a matter of big data, however, but also of the possibilities for processing them. Somewhat like the telegraph during the 19th century, new techniques — nowadays connected devices and sensors or more sophisticated means of measurement — are forcing researchers to address the tricky question of processing data that bring new information but do not “naturally fit” into their models. This problem is not new; we need but mention the assimilation of data from satellites. Handling it requires a capacity for processing data to fit them into conventional frames of representation. Might sensors, when seen from a different angle, not be a means for the on-board processing of data so that it can be taken into account? How to incorporate a maximum of the “intelligence of the processes” as early as possible in the data-collection phase? Given the mass of data collected by the new information systems, which procedures to use to validate the data (not to mention questions about the liability of the parties involved)? How (and to what degree) are data-laden observations to be processed if the data might be less rigorous or satisfactory than usual but if their huge quantity makes up for this lack of quality? The big data, now being collected thanks to digital technology, are awaiting methods of analysis for making sense of them.

In passing, we wonder whether this might be an opportunity for “participatory action research”,[8] as it spreads beyond the natural sciences (where it has existed for a long time now), to benefit from tools for collecting, exploring and interpreting data.

The goal of merging data from different sources is to provide an overall description of a system by taking into account measurements collected in various ecosystems. Tools for assisting decision-making, notably about environmental, natural or anthropic risks, could thus be proposed. Data bases would have to be gradually built that nurture the associated expert systems and quantify their performance.

[8] François HOULLIER (ed.), *Les Sciences participatives en France. État des lieux, bonnes pratiques et recommandations*, report to the ministers in charge of Education and Research, Paris, February 2016. Available via http://www.sciences-participatives.com/Rapport.

One facet of big data is the issue of open data, laden with questions about the processing and uses of data and about the business models of the parties involved. As we see, digital technology is a disruption in the realm of data that has, in turn, affected the persons involved in research, monitoring and observation. This disruption creates a requirement for further advances in digital technology in order to bring the stream of data under control.

We should stay alert lest the GAFA (Google, Apple, Facebook, Amazon) intervene and annihilate the work of the scientists and technicians who have rigorous criteria for validating the data collected and processed. The new players seem to want to take their place without fully assuming responsibility for what is produced and the related requirements.

Let us hope that all of this will wind its way into a virtuous circle. Confidence in big data and the algorithms used to process them will become the key issue for study and debate, this confidence being necessary for the application of responsible ethical principles. At the core of this issue is the harmonious combination of "authorized" data and of "big" data so as to obviate sterile debates and improve the understanding of the phenomena under study by all categories of the public.

A last point: it seems to be taken for granted that research on the environment is at the service of public policy-making. This research seems to be intended to shed light on the choices to be made by decision-makers or to alert them about critical situations. We must not, however, lose sight of the gap between research paradigms and public regulatory practices. To take an example: learning about the ocean and the complexity of its ecosystems is one thing, but drawing from this knowledge the tools for steering a course and monitoring phenomena (as under the Marine Strategy Framework Directive) is something else.[9] How to extract from data and models the right indicators? How to propose tools for making simulations of decisions and following up on them over time? Once again, the power coming from the digital realm is the key to this formalization and then to everyday monitoring for the purpose of apprehending the indicators of a "good" state of the environment.

Outside research, questions arise about organizations, markets, business and economic development. Means must be pooled to see to it that different communities will have access to big digital installations. In parallel, participatory action research, well-known in the physics of the atmosphere, is bound to develop and enable stakeholders to better pool and share know-how. An economic issue is to know who will be using these data — and will be using them not just to monitor the environment but also to manage it and restore it to a good state. These various trends are a source of innovation (for example, in applications related to big data and the Internet of things, or, more conventionally, in sensors or diagnostic tools).

In France, two research "alliances" are busy on these problems: Allistène for the information sciences (computer science, embedded electronics, the processing of signals and images, the human and social sciences) and AllEnvi for the environment (rural development, the Earth sciences, climate science, biology, ecology, physical chemistry, agronomics, economics, the social sciences, etc.). These two alliances have worked together, and this joint work should be extended to multidisciplinary teams that will explore the questions investigated by these disciplines as well as the implications of the constant back-and-forth movement between data and their processing.

The UN's sustainable development goals provide a framework for studying the state of the planet and the actions to undertake. Although the goals do not form a research program, several of them do imply research on the environment, which will provide findings for reaching them. These sustainable development goals hint at the need for a tight complementarity between the environmental sciences and the digital tools for collecting and processing data and for building models. In other words, an alliance between ecology and the digital sciences is a requisite for coping with the coming crises. This alliance is not to be seen passively, as being self-evident. We should see it as an essential for ushering in other forms of understanding and other practices.

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[9] Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive) available at http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32008L0056&qid=1507645555558&from=FR.