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Research article

Geo-hydrological Data & Models

The Anthropocene is shifting the paradigm of geosciences and science

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Abstract. Noting that humans are affecting the Earth's envelopes, with geosciences becoming inseparable from social sciences and humanities, and acknowledging the increasing use of the word Anthropocene, the authors of this paper explore the possibility of a scientific paradigm shift. (1) Since the 17th century, modern science has developed in a context of naturalist worlding that favors its hegemony over other modes of existence and its paradigm of a quest to define the laws of nature. (2) Various manifestations attest to the emergence of a paradigm of knowledge diversity and the unravelling of the naturalist worlding. (3) The current boom in participatory science is a sign of this paradigm shift: through the fundamental changes to the Earth System that refer to it, the Anthropocene forces science to move towards action and interact with a society involved in adapting to changes and concerned with the threats to its territory's habitability.

Keywords. Anthropocene, Scientific paradigm, Complexity, Plurality of worldings, Participatory science.

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1. Introduction

The aim of this article is to examine whether the context of the Anthropocene influences science and its universalist paradigm. The authors are neither specialists in philosophy nor in epistemology. Yet curious and aware of the importance of this issue in their own work, they are engaged in a reflection and an analysis of their practices and of specialized publications. The editors of this journal [de Marsily and Chabaux, 2020] have recently published an editorial reflecting their decision to broaden their editorial policy beyond the traditional fields of Earth sciences through the publication of articles dealing with "planetary sciences" in a broader sense. Encouraged by this editorial, the present authors are delighted to share their thoughts with the readers of the journal "*Comptes Rendus Geoscience*".

Our first reflection concerns environmental risks which have been present in all areas of life for several decades. As early as 1980, de Marsily [1982] reported that "the rapid progress of technology has made our world increasingly fragile, so that unforeseen local

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events may have deleterious effects on an entire country or even a continent" in his introduction to "Predictive Geology with emphasis on nuclear-waste disposal". He wrote this statement soon after the Seveso disaster in Italy, which prompted the adoption of legislation on the prevention and control of such accidents. The so-called Seveso-Directive (Directive 82/501/EEC) was later amended in the light of lessons learned from subsequent accidents. The future has proven de Marsily right. Since then, risk is commonly invoked in all scientific fields on a territorial or a global scale. The scientific community has been increasingly aware of the need to address the risks associated with what is commonly known as the Anthropocene.

The word Anthropocene first appeared in the discourse of globalisation during a scientific conference in 2000. The chemist and Nobel laureate Paul Crutzen suggested its use because he found that the extent of human activities was such that the creation of a new geological era was needed [Crutzen and Stoermer, 2000].

The word has followed two distinct paths since then. The first being an academic path within the Subcommission on Quaternary Stratigraphy of the International Union of Geological Sciences. The Anthropocene remains a topic of the active study of a working group charged with determining the distinction of a new geological time unit, based on the human impacts identified in geological records. Members of this working group argue for an Anthropocene epoch distinct from the Holocene [Syvitski et al., 2020, Zalasiewicz et al., 2015]. The argument considers changes in the state and functioning of the Earth System that are (1) beyond the Holocene's range of variability, and (2) driven by human activities and not by natural variability [Steffen et al., 2015]. This epoch started during early years of the 20th century [Haustein et al., 2019].

The second path is the use of the word by society at large, including scientific communities. The frequency of occurrence of the keyword "Anthropocene" has steadily increased in scientific publications since 2002. In 2018, it reached about 0.4, i.e., 40 occurrences per 100 publications [Gemenne et al., 2019]. Its frequency parallels that of "Earth System", which was at 0.55 in 2018, whereas this keyword was already well established in scientific publications in 1977 with a frequency of 0.02. This popularity illustrates the need for a distinction. Many alternative names for this era have been suggested, including those proposed by Haraway [2015], who, while highly critical of it, recognizes the usefulness of the term "Anthropocene." This word provides a platform to gather information and current preoccupations. Thus, the absence of an official definition from the academic geological community does not preclude the fact that this term can engage and encourage scientific thought and work.

In this paper, the word Anthropocene is used to define the period of history during which humans have become active agents in the planetary system, capable of hindering the physical mechanisms governing the way the ecosystems function in the general world [Descola, 2015, Steffen et al., 2011]. The issues we raise are the following: the hole in the ozone layer, global warming with all its consequences, the erosion of biodiversity through the extinction of animal and plant species on the planet's surface, and health considerations, with humans poisoning themselves through their own activities [Grau et al., 2022]. We could then read in the Anthropocene a *mise en abyme* of our own vulnerability, or to quote Serres [2020, p. 8]: « Nous avons récemment appris, au risque de notre survie, que nous dépendons désormais de choses qui dépendent de nous ».[1]

This article is divided into three parts. The first part reviews few scientific paradigm shifts in the past. It highlights the extent to which science and the work of researchers are embedded in the way societies deal with technology and the environment. It reminds us that abstract universalism dominates the paradigm of Western science and the relationship between humans and environment. Part one leads the authors of this article to conclude that a shift in the scientific paradigm is a valid assumption in view of the extraordinary impact that human activities have on the environment.

The second part "Towards a new scientific paradigm: knowledge diversity" explores how the encounter with other non-Western cultures leads us to question the universal, where it seemed to be most established, i.e., that science excludes contingency, and to explore how the context of the Anthropocene

[1] Our translation: "We have recently learned, at the risk of our survival, that we are now depending on things that depend on us".

leads towards a more humble, more inclusive science, more responsive to the singularity of beings and the diversity of forms of knowledge.

The third part "Strengthening participative science in the context of the Anthropocene" considers citizen involvement in the changing conditions of the Earth's habitability as it seems necessary to mobilize all spheres of society. It is based on a review of publications and on our own practice within a recent group dedicated to "Science and Society" [Mitja et al., 2021] established in the Espace-Dev research unit.[2]

2. Review of few previous scientific paradigm shifts

Targeting the scientific paradigm shift on the face of Anthropocene calls for the exploration of few of the paradigm shifts that have preceded this period. This part spells out a few examples. It demonstrates the relative banality of such shifts as their occurrence is relatively high. It also highlights how the legacy of some of these changes constitutes obstacles to change (the concept of the universal, positivism) while, on the contrary, others are breakthroughs that favor it (the theory of evolution, the concept of paradigm shift).

2.1. *From the concept of the universal to the laws of Nature*

In the philosophical tradition associated with Plato and Aristotle, intellect had the power to reach the very essence of things beyond their contingent appearances, and translated this power into concepts, explains Stengers [1991], an expert in the philosophy of science. Intellectual knowledge was therefore naturally relevant, free from passions and doubts, and accessible to any being endowed with intellect.

At the height of modern science, the concept of the universal was developed by many authors [Jullien, 2016, p. 8]. That it was a requirement of thought developed by classical Greeks was the source of its immense efficiency in Europe. The Greek "logos" of the centuries preceding the Common Era, writes Cassin [2016], a philologist and specialist in the rhetoric of modernity, is the starting point for the claim to universality. François Jullien explains that science in Europe was founded on the fact that the abstract universal constituted knowledge. He specifies the following points: (i) "l'opinion commune envisage les choses sur le mode du contingent, c'est-à-dire de ce qui peut être autrement qu'il est" while (ii) "la science envisage les choses sur le mode du nécessaire, donc de l'universel, c'est-à-dire de ce qui ne peut être autrement"[3] [Jullien, 2016, p. 18]. The universal laws of nature have become an essential foundation of science in connection with this concept of the universal and of the evolution of a geographical view of the world. In the Western Middle Ages, the importance of religion and Catholicism made Jerusalem the centre of the world [Clerc et al., 2019]. The importance of this vision is necessary to understand the major role played by subsequent discoveries. Copernicus (16th century), followed by Galileo, Kepler and later by Newton reversed this perspective by considering the Earth as part of a larger system. To define this larger context, Galileo used the special language of mathematics. This language, later mobilised by physics, makes it possible to decode this universe and extract its fundamental laws. It is from this universal that classical Europe, transposing it from mathematics to physics (Galileo, Newton), conceived the "universal laws of nature" with the success we know.

2.2. *Positivism driven by industrialisation and faith in progress*

Developed during the 19th century, positivism continues to a large extent to permeate present-day science. Auguste Comte [Mill, 1868] developed this philosophical doctrine in the early days of the Industrial Revolution. As presented by Stengers [1991], the example of chemistry shows its transformation from

[2]Espace-Dev research unit: Space observation, models and actionable science, https://www.espace-dev.fr/.

[3]Our translation: (i) "common opinion envisions things in the mode of contingency, that is to say, of what can be otherwise than it is", and (ii) "science envisions things in the mode of what is necessary, and therefore of the universal, that is to say, of what cannot be otherwise".

a science of nature into pure science. Chemistry became a “real” and powerful science in the 19th century after discovering the idea of chemical combination between a limited number of unit types. Prior to this, chemistry was a labyrinth of varied, poorly reproducible processes because it used non purified products. Industrial development enabled chemistry to work with pure products—it created its own components with properties that were independent from circumstances—after economic and social transformation led from craft to large-scale industry.

Positivism went beyond the strict framework of science to spread to the institutions of the Third Republic and into society itself [Weber, 1899]. According to positivism, scientific knowledge is made up of laws based on experiments, which one tries to generalize.

With the Industrial Revolution, the Western model imposed itself everywhere. With the help of science and technology, it sought to encourage humans to transcend their dependence on nature. Latour’s illuminating exploration of Hobbes’ *Leviathan* [2015, pp. 194–198] is quite explicit on this point.

Since the Renaissance, European powers have gradually built up a power structure that dominates the planet, with transportation and trade networks gradually covering oceans and continents. This was accomplished by an extremely small fraction of the population within the power structure, as well as by harnessing available energy. When the mastery of fossil fuels allowed European nations to strengthen their dominant positions, acquired through several centuries of colonial domination and capitalism [Chakrabarty and Chalier, 2018], a new relationship with the world came about.

The idea of progress became a source of salvation, and the human became superhuman in the West, and beyond. The impact on the planet then became increasingly important, leading to the modification of the planetary system, which had been in a state of relative equilibrium throughout the Holocene. Today the system is about 1 °C warmer with a degraded biosphere. If crossed, the threshold of around 2 °C makes self-reinforcing feedbacks possible. Even if human emissions were reduced, these feedbacks could then cause continued warming, the boundaries and implications of which are still formidable and unknown [IPCC, 2022a, Steffen et al., 2018].

2.3. *Time, chance, and interdependence come into play*

In the 19th century, a major revolution in scientific thinking took place [Nouvel, 2020, p. 279]. Science acquired a new paradigm. Time changed Nature and gave it a narrative pieced together in Lyell’s “Principles of Geology (vol 3)”, [2019, first published in 1833], captioned “Being an Inquiry How Far the Former Changes of the Earth’s Surface are Referrable to Causes Now in Operation.”

Darwin, who entertained a friendly relationship with Lyell, incorporated this new paradigm into his theory of evolution. With his *On the Origin of Species*, Darwin [1859] wrote the first scientific discourse on origin. Pascal Nouvel specifies that, before Darwin, “le vivant ne peut s’expliquer qu’en faisant intervenir une causalité finale (descendante), une intention… parce qu’il est inconcevable que le temps, si étendu qu’on puisse imaginer qu’il fut, ait pu produire les formes vivantes que nous connaissons"[4] [Nouvel, 2020, p. 269].

Darwin's work initiates several breaks [Hoquet, 2009]. Nature obeys laws that are not entirely reducible to mathematical laws, and chance comes into play, a step away from the trend initiated in the 17th century. Moreover, humans lose their exceptional status: species emerge only through a process of progressive differentiation. Finally, this differentiation establishes a kinship between species. We believe that these breaks are essential to build a new scientific paradigm in the face of the Anthropocene (cf. part 2).

2.4. *"Paradigm shift": a concept that facilitates change*

In the second half of the 20th century, the physicist and philosopher Kuhn [1970] introduced the concept of "paradigm shift". The paradigm shift may concern a minor modification, such as the use of an instrument. It can also concern a major change, requiring a new mode of narration, which is what we are exploring here in the face of the Anthropocene.

The depth of change brought by this concept can be substantiated in several ways. First, this concept appears today as necessary to the scientific community which uses it widely. For example, this expression has an occurrence of more than 400 per year since 2017 in titles of documents referenced in the "Web of Science" database.[5]

In essence, this concept encourages a rethink. It is no longer a value judgment of what true science is. It is not (or no longer) a question of moral order or of the absolute opposition between science and opinion. It is the context of production itself that is considered [Stengers, 1991].

For Kuhn, scientific discourse is linked to the community and the context in which it is produced. A paradigm revolution is therefore an evolution of the way of looking at an object from a new conceptual frame of reference. For the scientific community, sharing a paradigm means "seeing as" and this community that "sees like" will then come together to share an intense interest and work.

A paradigm shift occurs when the framework of thought is confronted with too many anomalies that can no longer be ignored and that lead to the formulation of new hypotheses and concepts to apprehend differently the questions that remain unresolved. A phase of crisis is characterized by an effervescence of new common frameworks proposed and questioned until a new paradigm gathers enough members of the concerned community to succeed in its adoption by the majority, to then return to a phase of stabilization. In this sense, the shift from geocentrism to heliocentrism mentioned earlier, or the theory of evolution, constitute paradigm shifts, because they upset our representation of the world and of the place of humans in it.

The establishment of this concept of paradigm shift is part of a period in which systems thinking and the complexity approach have developed as a critique of approaches that had been inherited from positivism. Considered too linear and analytical, these approaches nonetheless persist. Bourdieu [1976, 1997] has widely discussed and underlined the limits of a science that was considered objective, as stemming from the heritage of 19th century positivism [Mill, 1868]. The knowledge produced must be considered in its context: politically, socially, and historically. Furthermore, Daston and Galison's [2012] magisterial contribution to objective science leads us to identify how each major regime of thought defines in its own way the aspects necessary for the acquisition of proven knowledge [Latour, 2012b].

Popper [1963] argues that the aim of science is not so much to state the truth as to construct certainties from the demonstration of what is false. Thus, the scientific community does not have to claim to hold the truth, but can, on the other hand, object that such and such a proposition is false: a scientific theory is then true until the demonstration of its errors is established, or to use Kuhn's terms [1970], until a paradigm change intervenes.

2.5. *Conclusion on previous paradigm shifts and transition*

Today scientific knowledge is still mainly based on the Western paradigm of the abstract universal;

[4] Our translation: "the living can only be explained by involving a final (descending) causality, an intention… because it is inconceivable that time, however extensive we may imagine it to have been, could have produced the living forms we know."

[5] https://www.webofscience.com/wos/woscc/basic-search.

however, scientific knowledge has undergone profound changes proving its capacity to develop new frameworks. Not least of these changes is that science is one mode of existence among others—with its own forms of veridiction—and that this mode of existence does not have to be hegemonic [Latour, 2012a, p. 79–104; Latour, 2022]. The environmental history of political ideas shows that the will to modernize has been expressed in the form of a double injunction since the 17th century: one oriented towards abundance, the other towards freedom [Charbonnier, 2020, p. 41]. The challenges faced by science today require a fine understanding of the complexity of the situation, as this article aims to demonstrate.

In the following Section 3, we highlight a few milestones leading to a new paradigm, capable of making science a lever for action in the context of the Anthropocene. The current period marks an essential breaking point for humanity [Hamilton, 2016].

3. Towards a new scientific paradigm: knowledge diversity

In the present section, we deliberately examine the scientific discourses and emerging concepts likely to fuel a profound and far-reaching change in scientific thinking and practice. If, as Bouleau [2017] attests, 90% of science is still positivist, the present exploration deals with the remaining 10% that opens the horizon. The evolution of the positioning of science in the context of the Anthropocene and the conceptual and paradigmatic developments that are taking place, open up a necessary dialogue with the other terrestrials, to use Latour's word [2021]. Whatever the scale envisaged, it will be a matter of questioning science in the face of otherness.

3.1. *Geographicity and recognition of the other*

We have mentioned Kuhn's framework of thought about paradigm shifts in science earlier; we now focus on the case of "Man and the Earth" [Dardel, 1990, first ed. 1952]. As early as the 1950s, Dardel wrote that the superiority of modern man over the surrounding world seems an insurmountable obstacle to a sincere harmony with the forest, the sea, or the mountains [quoted by Raffestin, 1987].

Unnoticed at the time of its publication, this statement was later questioned in the 1970s. It now deserves to be considered in the corpus of resources facing the Anthropocene. Why did Dardel's work go unnoticed? It emerged in the post-war context when geography was then largely oriented towards the neo-positivist theses developed by the Vienna Circle, who at the time exercised a strong influence on the social sciences [Hempel, 1942]. This movement, born after the First World War, continued in France, Dardel's country, with the development of the "New Geography" after the Second World War. The aim was then to contribute to the reconstruction of the country. Legitimizing the scientific character of geography involved nomothetic approaches that made it possible to establish universal laws. Raffestin [1987] explains that Dardel's tragedy is to have been one paradigm ahead of his contemporaries: « Formé au paradigme du « voir », il a écrit au moment où triomphait celui de l' « organiser » alors qu'il postulait celui de l' « exister ».[6]

This paradigm proposed by Dardel [1990, first ed. 1952] is what he calls geographicity, which is defined as: « connaître l'inconnu, atteindre l'inaccessible, l'inquiétude géographique précède et porte la science objective. (...) une relation concrète se noue entre l'homme et la terre, une géographicité de l'homme comme mode de son existence et de son destin »[7] [quoted by Raffestin, 1989]. Dardel [1955], influenced by the work of the anthropologist Leenhardt [1985, first ed. 1947] in New Caledonia, and by Heidegger's philosophy, put forward the idea that the human being is inseparable from his space; meaning there is "an existential relationship" in which everything that surrounds the human being participates in his structure and his substance. These ideas obviously distanced Dardel from the positivist postures of the science of his time. Years later, his proposition to rethink the relationship between humans and the world by questioning this link was taken up by human and cultural geography [Berque, 1994, Bonnemaison, 1992, Collignon, 2002, Frémont, 1972,

[6] Our translation: "Trained in the paradigm of 'seeing', he wrote at a time when the paradigm of 'organizing' was triumphing, whereas he postulated the paradigm of 'existing'."

[7] Our translation: "To know the unknown, to reach the inaccessible, geographical concern precedes and supports objective science. (...) a concrete relationship is established between man and the earth, a geographicity of man as a mode of his existence and his destiny."

Lussault, 2007]. The critique and analytical contributions that followed made it possible to understand that the positivist foundations of science were not sufficient to grasp reality in all its complexity.

Today the question of the relationship between humans and the Earth—and the need to escape from an all-technological world, as analysed by Hoquet [2021]—are central to reflections on the future of societies, and on the place of science in this articulation between the particular and the general, the local and the global, the specific and the systemic.

3.2. *Complexity science, a revolution since the 1980s*

For several decades, the idea has been developed that natural or social systems are for the most part complex systems and can be studied as such. The reduction to simple linear causalities, practiced for centuries, is no longer relevant. A complex system is a system composed of many differentiated elements interacting with each other in a non-trivial way (non-linear interactions, feedback loops, etc.). It is characterized by the emergence at the global level of new properties, unobservable at the level of the constituent elements and by global operating dynamics difficult to predict from the observation and analysis of elementary interactions [Guespin-Michel, 2016].

This evolution emerged in the last quarter of the 20th century and opened avenues for scientific, social, philological, and philosophical ventures to deal with the intertwined crises of climate change, ecosystems, and human societies.

While Morin [1982] introduced the idea of complexity into the human sciences independently from mathematics, according to Guespin-Michel [2016], the complexity revolution was made possible by advances in computer science. Guespin-Michel [2016, p. 12] explained that the non-linearity of systems was initially ignored, not only because mathematics lacked the means to address it, but also because Cartesian thinking was an obstacle to complex thinking. The author concluded that a new rationality was emerging, based on a dialectical thinking of complexity, capable of studying natural systems and of fighting against the danger of irrationalism.

The complexity revolution may also be observed in the field of physics. In the introduction to his colleagues' interventions, the academic Derrida [2008] stated that, since its origins at the end of the 19th century, statistical physics has attempted to explain the collective behavior of many elementary objects based on their interactions. The aim was to predict whether a body was a gas, a liquid, or a solid. It gradually became apparent that increasingly complex phenomena could result from the collective behavior of many interacting objects, both in physics (fractures, avalanches, etc.) and in other fields (neural networks, gene and protein networks, the evolution of species, sociological networks, road traffic, financial markets).

However, many works that adopt the complex method encounter strong opposition. This has been the case with the Gaia theory "that views the evolution of the biota and of their material environment as a single, tightly coupled process, with the self-regulation of climate and chemistry as an emergent property" [Lovelock, 1989]. The philosopher and sociologist of science Latour [2015] recalls how this Gaia theory, that forces one to accept, or at least to explore the limits of the Earth, has found many detractors.

Today scientific discussions tend to abate, with articles such as Lenton and Wilkinson's [2003] and its discussion of all the specific terms of the controversy and its conclusion on how Gaia has contributed to the emerging field of "Earth System Science." Žukauskaitė [2020] synthesizes Haraway's [2016], Latour's [2015] and Stengers's [2015] work and invites us to rethink Gaia, not as an autopoietic unit, but as a complex and dynamic system of living things, including humans. Lenton and Latour [2018] present a convergence between the Gaia hypothesis, Earth System Science and humans' reflexivity as called for by Beck [1986]. They offer to create an infrastructure of sensors that helps track environmental changes along with social responses.

As the world is essentially complex, the concepts of complex real systems should be part of the arsenal of every and any scientist, but also of the thinking of every citizen [Guespin-Michel, 2016, Lévy and Lussault, 2003]. The very organization of scientific institutions based on disciplines must be revisited. The objective of reaching reality through the universal laws of a discipline is replaced by the objective of apprehending possible risks that can only be approached through the coupling of ecosystem dynamics and socio-cultural dynamics (i.e., all disciplines taken together). This advance towards complex thinking is therefore in the direction of a change in the posture of science and of its aims.

3.3. *Breaking down the silos of thinking*

This part explores the emergence of breaking down siloed thinking as attested in diverse studies: figuration [Descola, 2021], the concept of the "in-between" [Jullien, 2016, Cassin, 2016], origin and legal narratives [Nouvel, 2020, Bourgeois-Gironde, 2020, Notre affaire à tous, 2022].

The masterly synthesis of contemporary anthropological knowledge "Beyond Nature and Culture" [Descola, 2005 first ed., English ed. 2013] establishes four forms of worlding: i.e., four ways of composing worlds from the salient elements that the members of a collective detect or actualize in their surroundings. The key lies in the elementary mechanism of identification of the other. For any being that falls under his perception (fellow human being, animal, plant, thing, technical object, or other), every individual performs a process of "identification" that leads him to two questions. Does the other have the same interiority as me (or us)? Does it have the same physicality as me (or us)? The two possible answers (yes or no) to these two questions (interiority/physicality) lead to four possible combinations. Descola [2005] then establishes four categories of worlding: animism (yes/no), analogism (no/no), naturalism (no/yes) and totemism (yes/yes).

This synthesis not only presents a plurality of forms of worlding, but also shows that all four ways of composing the world are respectable. Science has so far been based on only one of these forms and is therefore invited to construct its approaches differently in the face of this plurality. Until recently, science, i.e., Western science, led to the view that non-naturalist populations were unenlightened and lacked the necessary basis for understanding the world in which they lived. In the rush to colonise, it was thought that these populations had to be civilised by teaching them the supposedly universal naturalist bases of knowledge.

Today, the challenge is to try to understand the multiple ways in which humans describe the world and what they do in it [Descola, 2011]. In response to Lacroix [2021], Descola states that it is interesting that the siloed nature of ontologies is now breaking down. The hybridity we experience today is only understandable if we can redesign the constituent parts that it combines. To do so, Descola's recent book [2021] led an investigation to identify the four ontologies of worlding in figurations, i.e., the objects they represent, and the relationships they depict. Indeed, figuration is, on the one hand, an operation common to all humans [Descola, 2021, p. 29] and, on the other hand, a doubly significant representation: as an icon and as an index of intentionality [Descola, 2021, p. 30].

A striking result of this investigation is the capacity of images to prefigure ontological and cosmological changes that are subsequently evident in texts that appear much later [Descola, 2021, p. 18]. In that respect, Europe offers a remarkable example. The dominant ontology in Europe had been analogism since Antiquity [Descola, 2021, p. 57] until naturalism took shape with the Renaissance, as attested in the writings of scholars and philosophers of the 17th century. However, naturalist ontology already appeared in painting at the beginning of the 15th century.

What about the current period? Do figurations of the 20th century augur new ways of seeing the world? Although we still lack the necessary hindsight, tangible leads are enlightening. With Cubism, at the beginning of the 20th century, entire sections of European images began to break free from the iconographic canons of naturalism, heralding the probable end of that cycle [Descola, 2021, p. 562]. Many contemporary artists evidence a great deal of ontological eclecticism in their work and their figurations fall under a plurality of worlding. Today's renewed success of Arcimboldo (1526–1593), qualified as an analogist bubble [Descola, 2021, p. 563], also illustrates our societies' appetite for a renewed way of seeing people and things [Parisi and Horvath, 2021]. Figurations are thus auguring the breaking down of siloed worlding.

The richness of the "in-between" emerges from sciences as diverse as biology, anthropology, Earth system science, philosophy, or philology. Jullien [2016] points out that in a world becoming globalized, there is no longer a "beyond" to dream of. It is in the "in-between" that resources are being discovered. The present resource is not that of identification, but of exploration, allowing another possible world to emerge. It will be necessary, he specifies, to leave the thought of being (ontology) and begin to think of the "in-between". Coviability, the concept of sustainable life for human societies within ecological systems, integrating interdependence and respect for others, fits well into this trend: it is in the "in-between" that the sense of self, respect for the other and interaction or interdependence develops [Coudrain, 2019].

The philologist Cassin [2016] praises translation for creating the passage between languages. As a competence in dealing with differences, translation can constitute the new paradigm of the humanities, each language being a web of equivocations. A single sentence, with its syntax and semantics, is indeed rich in perception, direction, and meaning.

Breaking down siloed thinking is also emerging from the analysis of discourses of the origin. Nouvel [2020] shows that there are four types of discourses: (1) descending from the complex to the simple: mythological discourses; (2) ascending from the simple to the complex: scientific discourses inaugurated by Darwin [1859]; (3) ascending and descending: rational discourses; and (4) neither ascending nor descending: phenomenological discourses. Nouvel [2020] links these four types of discourses to the four forms of worlding Descola [2005]. He emphasises the circularity of these discourses, as Descola [2005, 2021] did for the four types of worlding: there is no continuous evolution from one to the other, nor any superiority of one over the other.

The breaking down of the silos of worlding opens the way to thinking about the gap between the different ways of posing and solving scientific questions. Researchers can try to disrupt the scientific vision of the way we inhabit the Earth through three processes that are not totally utopian since they have already existed: how humans adapt to their environments, how they appropriate them, and how they express them politically [Descola, 2015]. Adaptation involves propagating the idea that our destiny is entirely dependent on billions of actions and feedbacks through which we generate the environmental conditions that allow us to inhabit the Earth; this theme is also widely developed by Latour [2021] and by Stengers [2019]. Appropriation means stressing that it is rather the ecosystems that are the bearers of rights and not solely human beings. Political representation is that of ecosystems.

In the wake of the "Natural contract" [Serres, 2020, first ed. in French 1990; English ed. 1995] which focused on the recognition of nature as a subject of law, there has been a proliferation of initiatives in recent years throughout the world, aimed at establishing legal rights of the environment [Notre affaire à tous, 2022, p. 141–414]. In the anthropocentric Western culture, characterized by a naturalist logic, this is a new positioning compared, for example, to the Universal Declaration [UN General Assembly, 1948], characterized by the absence of the word "nature" and which concerns only humans, in which non-humans do not benefit from a legal personality, nor from rights of their own. These changes are linked to the environmental crisis and to the position of civil society in favor of environmental protection [Notre affaire à tous, 2022, p. 7, p. 13–14]. Recent work on plant intelligence [Bouteau et al., 2021] provides evidence of the ability of non-humans to adapt and solve problems. The controversy surrounding the work on plants is reminiscent of decades of debate in the Earth sciences around the Gaia hypothesis [Lovelock, 1989]. Indigenous people who see humans as part of Nature are also the ones who protect it the most and lead the way towards its recognition as a subject of law [Notre affaire à tous, 2022, p. 8 and p. 105]. For example, Maori claims in 2017 led to the recognition of the Whanganui River as a subject of law. This case attests to the consideration of customary cultural values and a worlding different from Western universalism [Bourgeois-Gironde, 2020] in the establishment of law. There is something fundamental in this movement: the capacity to exercise a right for a human being in a place is no longer linked to his or her person. It is linked to his dependence on a place, that dependence being the legal source of the legitimacy of the occupation of space. This effects a reversal of the theory of appropriation.

Positions are emerging for science with the awareness that dialogue, understood as an attention to the "in-between", is necessary both between existing people and different ontologies. This can also be seen in traditional ecological knowledge (TEK). The rise of citizen science and the place it takes in the field of research is a matter of concern. In the following section, we develop the idea that it corresponds to a form of adaptation of science to the context of the Anthropocene.

4. Strengthening participative science in the context of the Anthropocene

The paradigm shift in science is also a consequence of the call from citizens to find in science, usable matter, questions, and answers to their own preoccupations. In this way, it is remarkable that IPCC reports changed from theoretical climate science to actionable science, especially in the last two assessment reports [IPCC, 2014, 2022b]. It is now more a question of delineating the gap between different ways of approaching one's existence and one's relationship to others (humans, groups of humans or non-humans) than of seeking a universal truth which in any case is not universal.

Scientific knowledge on the state of the environment has an impact only if society is informed or concerned by this scientific knowledge and puts in place decision-making mechanisms [de Marsily and Lallier-Vergès, 2015]. This calls to mind the deeply politicized nature of the environmental issue at a time when the need to reform our lifestyles and thinking patterns must take place without further delay. Humanity, a victim of itself, must face these changes while realizing that the most socially and economically vulnerable are the first victims of these changes. If the notion of a risk society, born in the 1980s [Beck, 1986, Perretti-Watel, 2010], called for risk to be considered, this notion is now outdated.

Uncertainty [Reghezza, 2015] and threat are now taking hold [Bourg et al., 2013]. They are part of everyone's daily call for collective action and the scientific community has a role to play. This section presents the specificity of citizen science, its growth, and examines the opportunity of this activity to face current challenges.

4.1. *The specificity of citizen science*

Dias da Silva et al. publication,"Review on citizen science in ecology and the environment" [2017] is a foundational document that clarifies the variations of terms used to designate these sciences, or the diversity of forms that they can take. In this paper, we focus more specifically on the usefulness of citizen science and the very concrete reasons that lead us to see them as a form of adaptation to the context of the Anthropocene.

Citizen science projects combine the knowledge of scientists (expert knowledge) with the knowledge of non-scientist professionals (local or lay knowledge) [D'Arripe and Routier, 2013, Wynne, 1999]. Non-scientist professionals are citizens who may be involved in one or more stages of the scientific research process: the definition of the research project, the development of the methods used to answer the questions posed by the project, the collection of data and/or their processing, the publication of the results, and finally the dissemination of results [Godrie and Heck, 2021]. The co-production of knowledge between citizens and scientists begins by a negotiation and results in a different way of doing science [Billaud et al., 2017].

Participative research projects need time and appropriate means and methods [Carrel, 2006]. They can be hindered by certain obstacles, such as the abandonment by, or the disinterest of citizens [Conrad and Hilchey, 2011]. To overcome these problems, participatory research projects should respect certain operating rules: consensus on objectives, clear definition of everyone's participation and funding. The specific challenge lies in refraining from depreciating the knowledge produced by the different participants, so that trust and dialogue allow the most relevant questions to be raised by the group as a whole. Researchers are, for their part, responsible for ensuring that scientific rigor is respected so that the results can be operative.

Citizen science covers a very wide variety of situations. In France, the greatest number of publications resulting from participatory research are in the fields of health and the environment [Storup, 2013]. Research projects dealing with concrete problems affecting civil society, with results likely to improve living conditions, trigger or accelerate citizen participation. In these cases, the knowledge of local citizens confronted with these problems can provide a complementary dimension with a better understanding of issues [Tengö et al., 2014].

In some cases, citizen science is essential as for example in New Caledonia (Loyalty Islands Province, French Republic) that has adopted an Environmental Code of the Loyalty Islands Province [CEPIL, 2019]. This code is based on the specific conception of life of the Kanak populations which stipulates that humans belong to the natural environment just like non-humans. As a result, certain elements of nature can be endowed with a legal personality with rights and can be represented by Kanak clans [Notre affaire à tous, 2022, p. 341–342]. Thus, lands under customary law are legally recognized. Research projects concerning these lands are enriched by a dimension of "negotiated knowledge" which should be considered in terms of otherness or intercultural dialogue. With the management of coastal areas, the classic framework for public action is inoperative since customary law supersedes state intervention on matters related to land. The involvement of local populations in management decision-making goes beyond any simple institutional “good practice”; it is a necessary precondition for action. In this context, work has been carried out on coastal erosion monitoring with the involvement of local populations. This is part of a science-participatory approach [Le Duff et al., 2020]: a more global reflection on coastal risk management, within the context of global warming and the proximity of the Pacific Ring of Fire, implying risks of tsunamis [Le Duff et al., 2016, Le Duff, 2018]. The population was waiting for answers and the exchanges that fuelled this work made it possible to develop a dialogue, both with the custodians and with the population. Customary authorities could then move forward on the shared understanding that discussions were ongoing about the future of the tribes established as close as possible to the coast. This joint reflection led to defining a management strategy shared by the customary, municipal, and provincial authorities and to the commitment of financial support for various development operations on the territory.

4.2. *Recent growth of citizen science*

To take into account the knowledge of the inhabitants of a particular location is nothing new. Empirical sciences from the 16th to the 19th centuries (botany, entomology, zoology, or astronomy) incorporated this knowledge into their corpora and datasets [Houllier et al., 2017]. At that time, they did not necessarily take into consideration the framework in which this knowledge was produced and mobilized, nor the full extent of its functions in the societies in question. More recently, social sciences have made individuals and societies their object of study. They have developed methods and protocols to encourage interaction and exchange with populations in order to apprehend this knowledge and to better understand its position, its representation, its use, and its practice in the social sphere. It meant trying to understand the meaning of this knowledge. But this knowledge is not, as we understand it today, “citizen science”, although these projects involved the participation of people. Citizen science is characterized by the reflexive positioning of the participants, and by a mutual and objective will to build a dialogue.

The strong growth of scientific publications on citizen science since the 2000s testifies to an increasing interest in the scientific community for this type of approach [Houllier et al., 2017, Juan, 2021, Storup, 2013] and highlights its usefulness in the current context. This growing interest could be read as converging with a concomitant societal desire to expand frameworks for democratic expression. Indeed, the 1980s were marked by the development of decentralization, social dialogue bodies, and administrative procedures for considering public opinion, particularly on environmental issues. This movement led in the early 2000s to the idea of participatory democracy that left more room for deliberation [Chlous et al., 2017]. During that same period, the discourse of international bodies on a community-based management of natural resources and, more generally, of the environment developed. The rise of citizen science was thus part of a context that helped shape it.

Thanks to the mobilization of the participatory approach, the OdyséYeu project on risks affecting coastal areas, such as coastal erosion and marine submersion, has made possible the acquisition of data over larger areas at higher frequencies, and with a greater reactivity than what conventional scientific production could have achieved [Cariou et al., 2021]. The usefulness of the approach goes even further because it also values the vernacular knowledge of the participants on local issues. What takes place between the participants is dialogue, listening, consideration, and an understanding of the respective positions of the participants. The COSACO project, which also deals with coastal risk [Ruz et al., 2021] emphasizes this valuing of vernacular knowledge.

On a national level, debates led by French representatives of different parts of society resulted in guidelines issued by the Economic, Social and Environmental Council [Blanchet and Jouzel, 2017]. At an international level, IPCC’s sixth report [2022a, 2022b] clearly recognizes the value of various forms of knowledge, such as scientific knowledge, but also indigenous knowledge and local knowledge, in understanding and assessing climate adaptation processes and actions to reduce the risks of human-induced climate change.

4.3. *Citizen science and the challenges of the Anthropocene*

Lenton and Latour [2018] clarify this challenge by putting forward an "infrastructure of sensors" to track the environmental changes and the latency of societal responses to these changes. Citizens, activists, and politicians would then collaborate with scientists, the goal being to assess where things are going wrong.

Climate change best illustrates how much the actions of everyone on Earth have an impact on the life of everyone else on Earth. Masson-Delmotte's review article [2020] provides a succinct scholarly summary on the current state of knowledge on climate change. The Club of Rome warned the world of the looming catastrophe in 1972 by a regularly updated publication [Meadows et al., 2004], and in 2017 more than 15,000 scientists confirmed the seriousness of the situation [Ripple et al., 2017].

The recent publications of IPBES and IPCC reaffirm that risks are still omnipresent in the lives of all humans and must be taken on board for the future habitability of the Earth. IPCC [2022a] sets the tone in its opening pages: "This report has a strong focus on the interactions among the coupled systems climate, ecosystems (including their biodiversity) and human society. These interactions are the basis of emerging risks from climate change, ecosystem degradation and biodiversity loss and, at the same time, offer opportunities for the future." IPBES [2019] delivers a similar message: Nature and its vital contributions to people are deteriorating worldwide.

In the tangible field of water, de Marsily [2009] explained the inescapable risk of famine with a population expected to reach 10 billion by 2100. Deficient food production in several regions highlights the need to share a common vision for the future and to plan for huge transfers of virtual water (agricultural production) to avoid inevitable famines.

The question is to move away from the current system, which is recognized as unsustainable in the long term, to another system which has yet to be invented, through sustainable transitions in sectors such as energy, food, and transport [Markard et al., 2020].

This challenge requires a global mobilisation, and to do so demands a detailed understanding of the complexity of the problem. Bouleau [2017], like Serrao-Neumann and Coudrain [2017], calls for a reorientation of science in its aims and methods. He proposes to introduce these fears into scientific work. This position of concern highlights the necessity of gathering knowledge from all available interpretative sources. The method then becomes participatory, between scientists from various disciplines and between scientists, citizens, and decision-makers.

Both citizens and researchers, as they share their different knowledge with each other, gain competence [Houllier et al., 2017]. For projects with data collection, citizen engagement allows covering a greater diversity of situations much faster (time of day, survey periodicity, seasons), which a research project cannot always achieve [Houllier et al., 2017]. The diversity of stakeholders brings added value through the multiplication of points of view [Brun, 2017]. Sauermann et al. [2020] argue that citizen science has the potential to help solve sustainability problems. This combination of diversified knowledge makes it possible to ask the most relevant questions, sometimes bringing to light new decisive elements that will be of great importance during the project [Juan, 2021].

Moreover, the knowledge of the citizens involved in participatory research who have been attached to a territory for many years can help in the interpretation of the results of the research project [Brun, 2017]. Beyond these appreciable advantages, motivated and enthusiastic citizens will be the bearers of the results acquired in collaboration with the scientists. The application of the results will be easier as these committed citizens become mediators. They are able to convince the general public and to participate in the urgent implementation of the solutions. Obviously, this participatory research does not exclude other types of scientific research [Godrie and Heck, 2021], but feeds off them, and vice versa.

5. Conclusions

The authors of this article have approached this work on the issue of paradigm shift in science and geoscience in the context of the Anthropocene as non-specialists. Bringing together the skills as biologist, geographer, and hydrologist, have placed ourselves in the "in-between" [Jullien, 2016] to explore the gap in our thinking habits in the face of an unprecedented upheaval: that of humans who have become a geological force modifying the Earth System through their actions.

The scientific syntheses on the climate or the biosphere by large organizations (IPCC, IPBES) insist on the urgency and the need to develop an intelligent and conscious society, capable of reacting. This is complemented by the contemporary work of human and social scientists, such as Descola, Haraway, Latour, Morin, Oreskes, Serres and Stengers. It is true that there is an increasing number of scientific programs and publications on the upheaval of the Earth's envelopes, but communication is clearly not enough to bring about necessary changes. The question becomes that of appropriating new worldviews.

The authors of this paper have examined the scientific paradigm established since the 17th century. It led to the establishment of universal laws of nature inherited from the classical Greeks. It also encouraged a sense of hierarchy with the hegemony of science over other modes of existence, such as art, law, politics, or religion. It is this form of power, based on a limited vision of a universal, that is questioned.

In today's scientific communities, the universal is gradually being replaced by the idea of a complex universe. The scientific community should meet the challenges posed by the Anthropocene. This situation calls for a collective responsibility for the current state of the planet. It demands a change in our vision, our practices, our relationship to the world and therefore our way of scientific work. History shows us that our scientific community has not only been able to evolve over time but has also been an actor in these changes. Different elements interacting with each other in a meaningful manner compose the world. We are witnessing conditions favorable to the emergence of a new paradigm and a gradual withdrawal of "normal science" to use Kuhn's words [1970].

Several developments attest to the emergence of a global, albeit still small scale, change in the scientific paradigm within scientific communities. The concept of paradigm shift developed by Kuhn [1970], has achieved great success beyond the scientific sphere. It facilitates the intrinsic transformation of research practices. It liberates from value judgement and morality. The complexity revolution is another thinking tool: a system composed of many different elements which interact with one another, in a nonlinear way and feedback loops. This thinking tool is spreading to many scientific fields, from the human sciences to physics.

The anthropologist Descola [2005, 2021] provides a basis for understanding that all humans conceive a world based on what they perceive as other. This author established four categories of worlding. Modern science developed in the 17th century based on only one of these worlding: naturalism, according to which what is non-human is devoid of interiority. His approach makes us understand how and to what extent it has become "normal" for humans to look down on objects and non-human living things. Descola's most recent work on images [2021] shows that the worlding limited to naturalism may now be coming to an end in favor of a plurality of ontologies. We consequently focused on exploring the other ontologies of worlding without value judgements and an openness to a multiplicity of ways of seeing the world.

Changing the frame of reference is no easy task, given that the time window is only a decade long and that what is left to be invented is considerable [Chakrabarty, 2018, IPCC, 2022a]. Citizen science could be essential, allowing many citizens to see science in action, with its complexity, its temporality, its challenges, its limits, but also its strength. It seems to pave the way for blending the efforts of the scientific community with the rest of society.

To the question we initially posed, the answer is that the sudden growth of citizen science in recent years responds to the need for a shared reality. Global warming and the so-called "crises" of the Anthropocene are still too often seen as catastrophic when in fact there is no turning back. There will be no post-disaster or "relief phase", no "return to normal". However, to initiate the necessary change, to initiate collective action, we need a narrative to drive us to a viable future.

Conflicts of interest

Authors have no conflict of interest to declare.

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