**Revue d'anthropologie des connaissances**

**16-2 | 2022**
**Controverses maritimes**

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**Electronic version**
URL: https://journals.openedition.org/rac/27795
ISSN: 1760-5393

**This article is a translation of:**
L'air collant en géodynamique - URL : https://journals.openedition.org/rac/26939 [fr]

**Other translation(s):**
Die Methode der klebrigen Luft in der Geodynamik - URL : https://journals.openedition.org/rac/27800 [de]

**Publisher**
Société d'Anthropologie des Connaissances

**Electronic reference**
Lucie Babel and Dominique Vinck, "The "sticky air method" in geodynamics", *Revue d'anthropologie des connaissances* [Online], 16-2 | 2022, Online since 01 June 2022, connection on 01 June 2022. URL: http://journals.openedition.org/rac/27795

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## Introduction

1 Researchers sometimes introduce fictitious entities into their calculations, models or theories (Thill, 1973; Winsberg, 2006; Lenhard, 2007). In geodynamics (a sub-discipline of geophysics) for example, many numerical models contain a component that is absent from the world as we know it: the so-called “sticky air”. In the geodynamics articles we read and in the words of those we met, this “sticky air” is conceived as being as viscous as partially melted rock and as light as air. It covers the whole of the Earth's crust in their models to a thickness of several tens of kilometres. It might appear surprising that this fictional entity — which would make sense in science fiction novels — is coming from scientists trying to describe and represent the processes affecting the internal structure of our planet. By reporting on what geodynamicists do with this fictitious entity, the article attempts to shed light on some aspects of modelling practices.

2 The “sticky air” trick raises an apparent paradox. While geodynamicists do have at their disposal numerical methods enabling them to model the Earth’s system as they wish, many do not implement these methods. Instead, they seem to prefer to integrate this astonishing hybrid and fictitious entity into their model in order to represent the

interactions between the Earth’s crust and the mantle. Before investigating further, this situation could made us think of that of students tampering with their data or their models to get to the result expected by the teacher. Far from that, the integration of components aimed at facilitating calculations is a usual, thought-out practice, which relevance and suitability is discussed between researchers. The singularity of the “sticky air” is hence not so much due to its fictitious character as to the representation that geodynamicists make of it. While most of these tricks remain hidden within the computer code, this one is named, drawn and displayed in articles and manuals. These representations allow us to follow it and thereby to exhibit a particular stage of numerical modelling.

3 It is during the transition from a conceptual model to a computer program that the trick and paradox in question arise. After having conceptualised the processes at work — in particular the convection movements of the mantle — the modellers we met translate them into a series of operations that can be executed by the computer in order to simulate these phenomena and thus study them. We shall see that this transition to the computer code is rich in negotiations. It is moreover far from being specific to geodynamics. All numerical models in the Earth and environmental sciences, including climate models which applications are of high societal relevance, require the writing of a computer code that can be read by the computer, in a language that is very different from that used to conceptually describe the systems under study. Nevertheless, this stage remains one of the least studied in science studies’ works devoted to modelling, as will attest the state of the literature presented in this article. However, the construction of the computer code has an impact on the final “product” — the numerical model, used as a research tool — the evaluation of which has in contrast been much debated (see in particular Oreskes, Shrader-Frechette & Belitz, 2004; Lahsen, 2005; Sundberg, 2011).

4 Through the case-study of the “sticky air method” used in geodynamics, this article proposes to explore more precisely what is involved in the little-studied process of making a model executable. What choices, what negotiations, what paths do modellers take in this field? In answering these questions, the article will follow the modelling trajectories taken by networks of researchers, oscillating between path dependencies (David, 1985) and attempts to deploy models towards new applications. Furthermore, it will attempt to identify the logics by which the “sticky air” has acquired properties — a name, a thickness, a viscosity, a visual representation — and has become an object of research in its own right in geodynamics. Our research is based on a mixed material composed mainly of the analysis of scientific articles published on the subject within the discipline, of manuals and reference books, as well as of interviews with actors in geodynamics. It also benefits from a fieldwork consisting of thirty semi-structured interviews with modellers in Earth and environmental sciences in several European countries and of participatory observation at conferences.

5 The article is divided into five parts. First and on the basis of our empirical material, we briefly present the main challenges of geodynamic modelling. We then proceed to defining the terminology we will use and situate our investigation in relation to existing STS literature. The case study and its methodology are introduced in the second part. The third part focuses on the apparent paradox arising from the use of numerical methods in our case-study. In doing so, this section explores the antagonistic dynamics that modelers face in trying to pursue their goal of modelling the motion of

the Earth's crust. The "sticky air method", which enables to deal with these antagonistic modelling trajectories, is presented in the fourth part. We follow the circulation of this trick in geodynamics and analyse more precisely what modellers do with the hybrid entity they created, through its naming, its visual representation and the control of its undesirable effects. Finally, the conclusion will return to what the use of the "sticky air" method reveals about the type of knowledge-creating practice that the stage of the construction of the computer code is.

## Numerical modelling and its use in geodynamics

6 *Earth sciences'* textbooks describe these sciences as an ensemble of many disciplines (geology, geochemistry, geomorphology, geophysics, climatology, hydrology, oceanography, among others), each with their own scope and analytical focus. Among them, *geophysics* is mainly concerned with the study of the internal structure of the Earth, its physical properties (*e.g.*, temperature, pressure, density) and the physical phenomena at play (*e.g.,* gravity, magnetism, seismic waves, mantle convection). The study of the evolution of this internal structure, particularly in terms of the movement of its components, is called *geodynamics*. Our case study is located within this sub-discipline of geophysics.

7 Researchers in geodynamics are interested in the dynamics of the interior of the globe and of its surface. Geodynamic research aims both at understanding the formation of existing terrestrial structures and to comprehend the mechanisms behind certain natural phenomena (volcanism, seismicity, *etc.*). Depending on the time scale and the depth considered, geodynamic research can have applications in natural hazard prevention, waste storage, geothermal energy and the identification of mineral and fossil resources. However, most of the research conducted in geodynamics — including the work presented in this article — falls under fundamental research. It is carried out within universities or research institutes and is publicly funded. While the societal justifications for funding sometimes relate to the prevention of natural hazards, the research projects we refer to have no direct applications in this respect; they aim at improving the understanding of particular mechanisms and of their interactions. The number of researchers in geodynamics is still very limited compared to the number of researchers in other Earth sciences disciplines such as climatology or hydrology. In Europe, where our research took place, researchers generally know each other and often share a common biographical element: a PhD or a post-doctoral research position at the Institute of Geophysics of the Swiss Federal Institute of Technology in Zurich (Switzerland) or a collaboration (research, publication) with professors affiliated with it. Competitive dynamics between research groups do not seem intense in this discipline. On the contrary, during our research we have acquired the image of a small, relatively tight-knit community, not divided by controversies and presenting a strong dynamic, focusing both on technical development and on the diversification of the applications of its methods (extended, *e.g.,* to other planets of the solar system). Collaborations between geodynamicists from different institutes and countries seem to be very frequent and diverse, and are reconstituted differently when new research projects are set up.

## Modelling as a way to compensate for the lack of data

8 Geodynamicists face a major challenge in studying the processes at play in the interior and on the surface of the globe: a tremendous lack of data. The only remains of the past dynamics of the Earth system are some of its consequences on the surface. The phenomena themselves cannot be observed by researchers, because of time scales considered (thousands, millions, even billions of years — on the scale of a human lifetime, the Earth’s crust and the mantle seem immobile) and the inaccessibility of Earth’s interior (the Earth’s crust extends to a depth of 50 km, the Earth’s mantle to 3000 km). The processes, their causes and effects must therefore be imagined, hypothesised and reconstructed (*ex post* and *ex situ*). One of the main tools used by geodynamicists for this purpose is the model. Three categories of models exist side by side and complement each other in this discipline: analytical models, analogue (laboratory) models and numerical (computer) models. This article focuses on the third category of models: numerical models.

9 In the following sections, we will use the terms modellers and geodynamicists alternately, to highlight the two sides of the encountered actors’ profiles. In this discipline, as in many others in the Earth sciences, numerical modelling does not fall within the scope of a dedicated technical staff. The geodynamic modellers we interviewed or whose work we read had initial training in geophysics, geology or geosciences, or even physics. Numerical modelling is now part of the *curricula* of these study tracks, but remains often optional. The modellers reported that they acquired most of their advanced modelling skills “on the job”, by discovering and manipulating models created by others.

10 Numerical models of geodynamics describe the movements of the Earth’s mantle and crust by resorting to fluid mechanics. Earth’s materials are not fluid at first sight, on a human scale. However, on a geological scale of more than tens of thousands of years, their behaviour is considered viscous — even that of the Earth’s crust. The basic equations of fluid mechanics (the branch of physics that studies the behaviour of fluids) can then be applied. The equations in question translate the conservation laws of mass, energy and momentum (these quantities are constant; if a quantity disappears somewhere, it must be found somewhere else). From a mathematical point of view, these equations belong to the category of “partial differential” equations, which are very common in physics and engineering. The unknowns (*e.g.*, temperature) in these equations are themselves functions that depend simultaneously on the behaviour of several independent variables. An important feature of the vast majority of these equations is that they cannot be solved analytically — that is, by manipulating the terms and symbols of the equations. The equations are so complex that for some of them (*e.g.*, the Navier-Stokes equations, central to fluid mechanics), the very existence of solutions has not yet been proven and is considered one the most difficult mathematical challenges. This challenge is even one of the “Millennium Prize Problems” of the Clay Mathematical Institute, endowed with one million dollars. Geodynamics researchers hence do not solve these equations, but try to approximate their solutions by means of computer calculations. To do this, they resort to *numerical methods*. These methods and the transformations they require of the modelled system are the focus of our investigation. In the following section we will look into existing

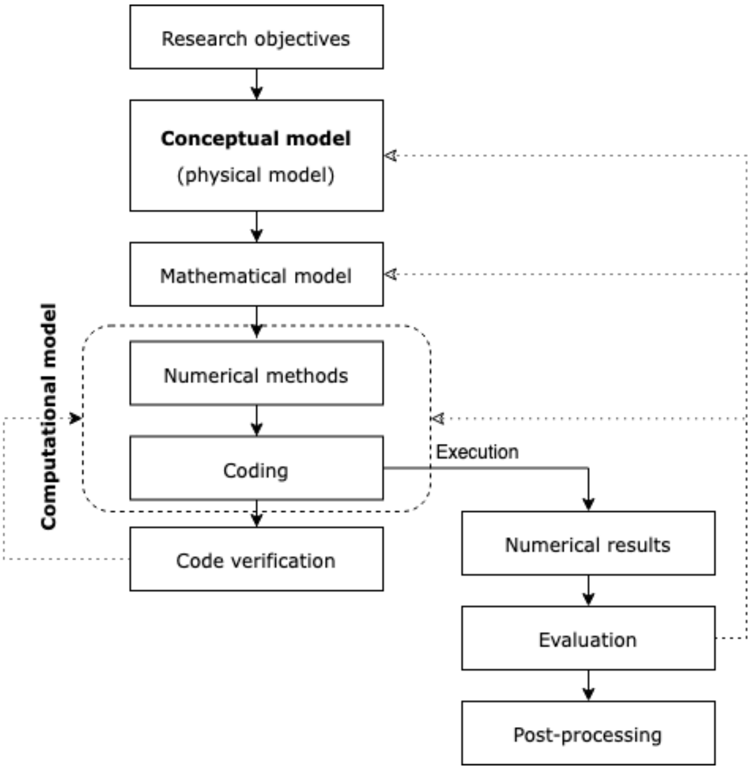
literature on modelling that can — or cannot — be of use for the study of these transformations.

## The different stages of the modelling work

11 To our knowledge, there is no work in science studies dealing with geodynamic modelling. Moreover, only few social science researchers have taken an interest in numerical modelling within the Earth sciences, regardless of the scientific discipline. These have primarily focused on numerical climate modelling, which raises major societal issues and is a subject of controversy in connection with climate change. This work is *a priori* relevant to the study of geodynamic modelling insofar as climate and geodynamic models have many points in common. Like geodynamic models, “general circulation models” of climate (GCM) are based on fluid mechanics; the challenge of approximating the solutions of the equations is shared; and the mathematical-computational techniques used for this purpose are similar. These mathematical-computational techniques and associated practices remain little studied and have been left on the sidelines by STS literature on modelling.

12 Our investigation focuses on a specific stage of the modelling process, which can be situated using the modelling process diagram (Fig. 1) frequently used in the geoscientific literature. We cannot expect this type of diagram to represent the actual practices of modellers, but the terminology it employs will be useful for the rest of this paper. According to this scheme, a numerical model is based on a *conceptual* model, corresponding to the qualitative representation of the system under study, its components, their characteristics and their interactions. A *mathematical* model translates this conceptual model into a system of equations, which are translated into a *computational* model that can be run on a computer. These three types of models (conceptual, mathematical and computational) correspond to different objects: the conceptual model usually takes the form of a sketch of the system under study[1] and reflects the researchers’ ideas, knowledge and assumptions about it; the mathematical model is composed of a series of equations; and the computational model is a computer code. This computer code, when executed (or “read”) by the computer, transforms a set of data, corresponding to the variables considered by the model, into results that are then visualised by the modellers in the form of graphs, maps, images or videos. The results are compared with existing data (from observations of the Earth’s seismic activity), existing representations (the “conceptual model”) or with results of other simulations.

Figure 1: Representation of the numerical modelling process



Flowchart adapted from Ismail-Zadeh and Tackley (2010, p. 16) representing the process of numerical modelling. The dotted arrows in the diagram represent the possible iteration loops, which are performed until the verification of the code and the model evaluation produce the expected results.

Credit: Diagram from Ismail-Zadeh and Tackley (2010, p. 16), adapted by the authors.

13 The evaluation of model results is precisely the step that has attracted the most attention from science studies authors, including science historian Naomi Oreskes, philosopher Kristin Shrader-Frechette and hydrologist Kenneth Belitz (1994), anthropologist Myanna Lahsen (2005), historian of science Hélène Guillemot (2009), philosophers of science Johannes Lenhard and Eric Winsberg (2010), Elisabeth Lloyd (2010) and sociologist Mikaela Sundberg (2011). This interest is linked to a context of political controversies targeting the reliability of climate model projections. Thus, the evaluation of numerical models, in terms of their practices, vocabulary, relationship to truth, reality or data, has been a major issue both within the scientific community of Earth and environmental modellers (*e.g.* Beven, 1993; Odenbaugh, 2005; Rykiel, 2006; Knutti, 2008) and in STS work on numerical models.

14 By contrast, the construction of the code leading to these very results has only been treated shallowly. Important books and articles retracing the development of a model in its political and institutional co-construction (*e.g.*, Armatte & Dahan Dalmedico, 2004; Dahan Dalmedico, 2007; Edwards, 2013) have taken an interest in it. Nevertheless, they most often proceed to present the main mathematical and computational principles guiding the construction of the code and analyse their evolution over time. The practices themselves have hardly been studied in depth. This mainly historical treatment of the computational model may convey an impression of linearity in the modelling process, of an absence of choice and of numerical techniques gradually prevailing because of their efficiency.

15 If we accept to move slightly away from Earth sciences, we can find in the work of anthropologist Matt Spencer’s (2012b) an in-depth ethnographic study of modelling dealing more deeply with numerical methods and computer code. Although the author’s analysis is primarily epistemological in nature, his research conducted in computational physics will be of interest to us because of the position it grants to numerical techniques employed in modelling, in relationship to the computer code and the notion of representation. Philosopher of science Tarja Knuuttila, sociologist Martina Merz and historian and philosopher Erika Mattila (2006) note that by engaging with numerical modelling, philosophers of science and STS scholars are moving beyond their former division of labour between the analysis of conceptual production and the study of experimental practices (Moreno & Vinck, 2021); the study of modelling brings researchers together insofar as modelling and simulation relate to both theoretical and experimental work (Dowling, 1999; Morgan & Morrison, 1999; Sismondo, 1999). The type of object we are investigating is a good example of this interaction between philosophers of science and STS scholars. Winsberg (2010), for example, discusses the “fictional” character of modelling, which will be relevant to question some of the practices surrounding the use of the “sticky air method”, presented below.

## Studying modelling practices: a distributed case study

16 The case study we present is part of a wider research on practices of numerical model construction in the Earth sciences. In this context, we attended two annual conferences of the European Geosciences Union (EGU) with an approach of participative observation, one of the authors of this article coming from these research fields. Bringing together more than 15,000 researchers over six days in Vienna (Austria), these conferences consist of several hundred uni- or multidisciplinary sessions. It was during one of the geodynamics sessions of the 2019 edition that we were confronted for the first time with the “sticky air method”. The session was a 90-minute short course on numerical methods, intended for young geoscientists who were not familiar with numerical modelling in geodynamics. The fact that the “sticky air method” was discussed in such a brief and general session tells us something about its relatively common status. The presentation did not stir up any reaction from the audience, even though it was about introducing a fictitious entity into the model.

### Empirical approach

17 Our aspiration to follow the practices — in order to report on the emergence of this fictional entity and on its uses — confronts us with a recurring methodological challenge in science studies devoted to modelling. As highlighted by Guillemot (2009) and Sundberg (2010), numerical modelling does not lend itself well to ethnographic observation. The activity of modellers, typing on their keyboards and clicking on their mice in front of computer screens, can remain particularly opaque to the observer. The incremental construction of models, often happening over several decades and in multiple production sites (Lahsen, 2005), further complicates the gathering of empirical data. Guillemot (2009, p. 276) thus considers that in modelling, “the description of the practices of the researchers inevitably involves their own discourse during interviews”. Confronted with numerical methods in computational physics, Spencer (2012b, p. 12)

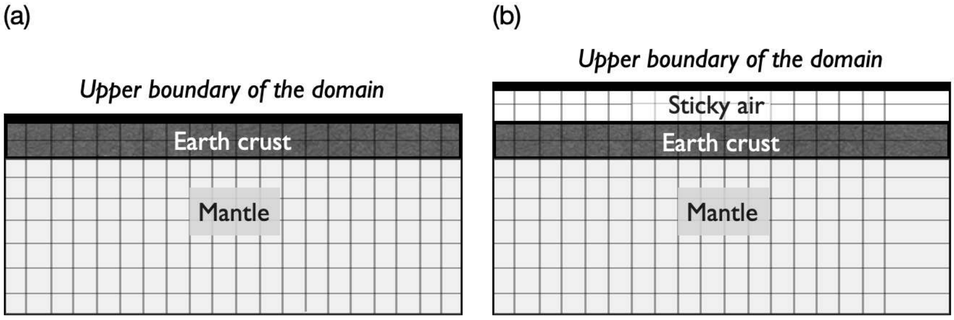
nevertheless refuses to limit himself to interviews, as he considers that their contents can only be understood if they are accompanied by a broader ethnographic approach. We shall agree with him here. An initial interview with one of the “sticky air” specialists quickly showed us that we would not be able to reach the level of detail required to reconstruct the practices by relying solely on these exchanges. Just as Spencer (2012b), we had to personally confront the technicality and specificities of this field of research. This investment went beyond mere reasoning; we had to learn to read and manipulate graphical representations and equations in order to cross-check and reconstruct. To do this, we made extensive use of the resources used by geodynamicists: scientific articles of this domain, manuals on geodynamic modelling and numerical methods, extracts from courses, but also questions submitted informally to geodynamicists and to a mathematician on mathematical and computing details that we encountered along the way. We were then gradually able to get close enough to the objects under consideration to discern choices, bifurcations and to discuss them during interviews. The process was iterative: the practices outlined by the geodynamicists during the interviews referred us to other articles and works on geodynamics, to other images and equations, which in certain cases led us to contact the authors. As we were not able to study situated practices — within a laboratory or in the course of action of a project — since what is being played out takes place in various places and points in time, it is thus through successive iterations in the materials of the survey and with our conversation partners that we progressively reconstituted their universe, their practices, their evolutions, their stakes and their friction points.

18 The anonymised geodynamicists to whom we give voice through quotes from our interviews all work in different institutes and countries, but have in common to have used the “sticky air” method in previous research projects. We have chosen not to reproduce excerpts from the correspondence with authors as it mainly concerned objects on the periphery of the “sticky air” method — the grasping and study of which were necessary for a better understanding of this technique, but which we do not develop in the article. Finally, the more general challenges of numerical modelling that we are led to take up are nourished by a fieldwork consisting of thirty semi-directed interviews with modellers in the Earth and environmental sciences in France, Switzerland, the Netherlands and Germany, which focused on the choice of certain model components and on the transfer of modelling practices; participatory observation at the European Geosciences Union (EGU) conferences in Vienna, Austria, in 2018 and 2019; and finally, numerous formal and informal exchanges with modellers, one of the authors being affiliated with a research group in computational geography.

## The case of the “sticky air” method

19 When it comes to modelling a system numerically, modellers agree both in textbooks and in their practice on the need to define the model *domain.* The model domain is the portion of space to be modelled and to which the equations under consideration apply. For two-dimensional modelling, which is prevailing in geodynamics, the model domain most often takes the form of a rectangle. In this case, it contains part of the Earth’s crust and mantle (Fig. 2a).

Figure 2: Representation of the model domain before and after insertion of the “sticky air” layer



Schematic comparison of the geodynamic model domain before (a) and after (b) insertion of the 'sticky air' layer. The model grid is composed of grid cells, each on which the equations under consideration are applied.

Credits: designed by Lucie Babel.

20 The “sticky air method” consists of adding a layer to the model domain on top of the Earth’s crust (Fig. 2b). This layer, known as “sticky air”, has both the density of air (zero) and a viscosity one hundred thousand quintillion times greater than that of air. No known element presents such a combination of contradictory properties. The “sticky air” layer is thus not intended to represent a physical “reality”; it is not part of the conceptual model, but only arises during the construction of the computational model. This practice allows us to focus specifically on this stage of the numerical modelling process.

## Representing a moving Earth’s crust: lock-in versus unfolding trajectories of numerical modelling

21 The “sticky air” method is not used in all geodynamic models. It only appears in models that include the interaction between the Earth’s crust and the underlying mantle. Interest in this interaction was motivated in the mid-1980s (see, *e.g.*, Hager *et al.*, 1985; Koons, 1989) by research showing that mantle convection could raise and lower the Earth’s crust in places[2]. Collective exploration of the interaction between the Earth’s crust and mantle accelerated during the 1990s as particularly detailed measurements of Earth’s surface deformations and motion were obtained (Burbank & Pinter, 1999). Since the late 1990s, numerous numerical and laboratory methods have been developed to dynamically simulate these movements (see Schmeling *et al.*, 2008).

22 In geodynamic models, the Earth’s crust generally is the upper boundary of the model domain (see Fig. 2a). This means that if the Earth’s crust is set in motion — which is the objective of most modellers taking into account the interaction between the crust and the mantle[3] — the model domain would no longer be rectangular as in our figure. It would be deformed at the top.

### Computational cost of numerical techniques

23 However, deformations of the model domain have a cost. In their models, geodynamicists divide the domain into small geometric entities and thus form the model *grid.* With the deformation of the Earth’s crust, all the elements of this grid are

also deformed. Compared to a fixed grid, many more calculations have to be performed and stored by the computer during the modelling process. For the modellers, the available speed of calculation and the storage capacity — far from being abstract entities — are material resources installed in research institutes and their socio-technical networks. The work then depends on the type of computers the modellers have or to which they have access, on their collaboration with the people who manage these computing resources and on the maintenance of the computers. How long can a modeller "run" her/his model before encroaching on the activities of other members of the institution or on her/his institutionally negotiated agenda (Fujimura, 1987)? Does the institute have access to the supercomputers of a national computing centre? These conditions relating to the infrastructure of modelling are omnipresent in reflections on the choice of numerical techniques. Historian Paul Edwards aggregates them by referring to "computational friction" (Edwards, 2013, p. 84). This concept includes *"not only the physical and economic limits on processor speed and memory capacity"*, considered and compared in scientific papers by referring to the "efficiency" or "computational cost" of numerical techniques, *"but also the human work involved in programming, operating, debugging and repairing computers"*. The concept of "computational friction" is not well known in geodynamics. The use of the notion of "computational cost" by geodynamicists during our interviews is nevertheless close to this broader definition and goes beyond the mere material resources used for calculation. It is also one of the first arguments spontaneously put forward by the modellers during our interviews to justify the choice of a method. It is to a "computational cost" including the programming work that geodynamicist A. refers when he rejects the usefulness of a deformable grid during an interview:

> For mantle convection models... you have so much deformation that you need to reset your (model) grid during the evolution, so that makes not much sense. (A., geodynamicist, 12 March 2020).

24 A. specifically mentions mantle convection models because not all geodynamic models concerned with crustal deformation do so on the same time and space scale. Mantle convection models study mantle dynamics to great depths and over timescales ranging from tens of thousands to millions of years. At these scales, the deformations of the mantle are so large that the programming difficulties of implementing a deformable grid seem insurmountable to the geodynamicists we spoke to. On the other hand, the "computational cost" is much more affordable when the models operate at smaller scales. Geodynamicist S., who also works on models of mantle convection, had been collaborating with what she calls "*earthquake people*", whom she considers a distinct community. Their models simulate processes lasting for only a few minutes.

> They never had any need for looking at methods that could accommodate a lot of deformation...This whole community also had never heard of "sticky air", because they don't need it... They don't look at long-term processes. (S., geodynamicist, 25 May 2021).

25 The problem of the unaffordable computational cost of the deformable grid is in fact specific to geodynamicists modelling mantle convection. It is to this group that we will refer for the remainder of the article when we speak of "geodynamicists" for the sake of brevity.

## Compatibility issues

26 The use of a fully deformable grid is not considered an affordable option by geodynamicists. In order to represent the movements of the crust, other modelling techniques have been developed. One of these, called the *Arbitrary Lagrangian-Eulerian Method* (ALE) and borrowed from engineering, only allows for vertical deformation of each grid element — which is much less costly in terms of numerical resources than if horizontal displacements were also to be calculated. However, not all computer codes are compatible with this kind of technique. Therefore, ALE, which allows partial deformation of the grid, is only used with the finite element method[4], since its main alternative (the finite difference method) requires the use of a completely fixed grid.

27 What limits geodynamicists’ room for manoeuvre is hence not only computational cost, but also choices made beforehand regarding the numerical method. The numerical methods condition the writing of the computer code, as they discretise (*i.e.*, cut up the model domain) in different ways. The “finite element” method approximates the results of the equations at each intersection (node) of the model grid, whereas the “finite element” method approximates the results of the equations over the entire surface of each grid element. This difference is so fundamental regarding the mathematical writing that modellers cannot switch from one to the other within the same model. Thus, a modeler using a finite difference model will be constrained by the mathematical writing to a fixed geometry, making it impossible to deform (even partially) the domain grid. We might therefore expect that all geodynamicists wishing to represent the movements of the crust would use the other numerical method (the finite elements method), allowing for deformation. However, this is not the case. Our research suggests several possible explanations for this apparent paradox, which are developed below.

## A legacy of numerical methods and models

28 Modellers do not necessarily choose the numerical methods they use. Most of the geodynamicists interviewed were using models designed by other modellers, which they had sometimes supplemented and modified. The case of geodynamicist S., a post-doctoral student, is an illustration of this. During her doctorate, S. worked on a model built by her thesis supervisors, as did all the other doctoral students in the research group to which she belonged. Each PhD student was assigned to develop a different piece of the initial code. During her first post-doc, S. had changed the model and used the one designed by one of her former professors. At the time of our interview, she was preparing to take up a new position a few months later. This new job would require S. to switch back to another geodynamic model. These successive changes were mostly dictated by her arrival in a new research group, in which a geodynamic model was a common working tool for all researchers. In this case, the modellers are accommodating the model used locally and certain initial choices made by their predecessors. S. often used the term “*legacy*” during the interview. She felt that the use of the finite element method or finite difference method was thus *“just a matter of preference, to some extent, of the person who is coding it [the model] up in the first place”*[5]. Because of the impact of this initial choice on the mathematical writing of the code (see above), what the geodynamicist S. describes as “legacy” takes the form of a path dependence (David, 1985) marked by its irreversibility (Edwards *et al.*, 2007). Reversing

the choice of the numerical method would require reversing the original model and rewriting it entirely; an undertaking which is not only very costly in terms of time and personal resources, but which also calls into question the modeller’s place within a network of actors articulated around a pre-existing model and its incremental development.

29 Geodynamicist S. displayed a mobility — between models, between numerical methods and also between research groups — that we rarely encountered in other interviews. She was aware of this singularity, and stated that she was known for repeatedly changing the type of model used. Across all disciplines of Earth and environmental sciences, the majority of the modellers we interviewed continued to use — sometimes up to two decades later — later versions of a model they had become familiar with during their thesis or post-doctoral research, or which they had helped to develop at that time. Modellers have often made such a professional investment (Pickering, 1985) in acquiring the know-how to work with a particular model that this investment reinforces its subsequent re-use. These observations also apply to numerical methods. On the basis of our interviews, we have shown in a previous article (Babel, Vinck & Karssenberg, 2019) that the repeated choice of a numerical method could also initiate a particularly lasting path dependency — due to the expertise acquired and the anchoring in a network of researchers using the same method. For those who have been trained in one of these methods, have experienced its constraints and have been able to cope with it, switching to a model based on another method can therefore represent such a significant investment that it can be a disincentive.

## “Unfolding” objects

30 One institution seems to have played a particularly important role in the shaping of modelling trajectories: the Institute of Geophysics of the ETH Zurich. This institute houses two very dynamic research groups (large number of researchers, multiple international collaborations, considerable number of publications). Almost all the geodynamicists we met or whose articles we studied had spent time in this institute. One of the institute’s professors has written a widely-spread manual on numerical modelling in geodynamics; we found this book in the offices of researchers we met and its re-edition was even the subject of a presentation considered as a “highlight” at the general assembly of the European Geosciences Union in 2019.

31 The two research groups at this institute are the instigators of two of the most renowned models in geodynamics. Both models are based on the finite difference method. This fact is far from anecdotal, as it means that a large research collective — composed of members of the institute, of researchers who have left but continue to use one of these models, as well as of external researchers collaborating with the institute on joint research projects — is locked into a modelling trajectory based on the use of a fixed geometry. We use the idea of a trajectory here as these models are far from being fixed in time. The models we encountered in the Earth sciences share with the models of particle physics studied by Martina Merz (1999) the particularity of being “unfolding” objects. Their permanent transformation responds to the aims of improving their efficiency, of removing instabilities and of adapting the computer codes to the evolutions of the available infrastructure. Additionally, the modifications can consist of extensions enabling model users to answer additional research questions.

Just as geodynamicist S. during her PhD, many researchers are working on extensions to the two ETH models. Because of the large number of versions developed in parallel, geodynamicist S. even said during the interview that she had never seen “*the real thing*”, by which she meant the consolidated, fixed model, devoid of the many branches added to its structure, each of which allows new research approaches and new applications. This characteristic deployment of the models we have studied often seems to respond to a strategic interest. Allowing additional research questions to be addressed helps to consolidate the competitiveness of the model and to maintain a stable or even growing network of users; it is also generally a condition for obtaining new funding. Sometimes, however, the models seemed to be developed outside the research group that built them. Modifications were then made by individuals or groups who had gained experience in the use of particular models and who wished to continue using them while adapting them to their current research.

32 These antagonistic modelling dynamics — unfolding or locking-in by inducing path dependences — allow us to better understand the at first sight paradoxical emergence of techniques such as the “sticky air method” within numerical models. The circulation of researchers and their relationships result in the constitution of modelling traditions, the limits of which spur innovation without overthrowing the original model. The “sticky air method” thus allows models to be unfolded towards new applications (a dynamic representation of crust-mantle interactions) without deviating from the locked modelling trajectory on which the models are situated (the use of a fixed grid). Along the way, we have hence become aware of the importance of taking into account the trajectories and relationships between researchers in order to understand the “choices” of methods they make and the processes of model consolidation at work.

## Introduction of a fictitious entity: the sticky air method and the dissociation of boundaries

33 As we saw above, models employing the “finite difference” numerical method have a completely fixed grid. In general, the upper boundary of the model domain (the upper side of the rectangle; see Fig. 2a) represents the Earth’s crust. According to the modellers, here lies the main pitfall when aiming at representing the movements of the crust, since this upper boundary cannot be mathematically set in motion. Our investigation shows that one of the most common solutions to what might appear to be a dead end is a geodynamic sleight of hand. If the upper limit of the (computational) model is no longer the upper limit of the (conceptualised) Earth system, the situation we outlined becomes in fact quite different. To separate the two boundaries, the modellers introduce a fictitious layer of sticky air. The two boundaries can then be treated separately: dissociated from the Earth’s crust (see Fig. 2b), the upper boundary of the model domain is now only an abstract boundary, required by the numerical processing but devoid of any physical meaning. It no longer needs to be set in motion. The Earth’s crust and its boundary with the mantle lie within the model domain, and geodynamicists can now represent the interactions between them using widespread methods[6] that are compatible with the use of a fixed grid.

## A fictional hybrid made of air and rock

34 The sticky air layer is therefore a trick to separate the two boundaries (Fig. 2b) and thus to use a fixed grid. Although not present in the conceptual model, this fictitious entity is nevertheless endowed by geodynamicists with physical properties, just like all the other components of the model: it has a density, a thickness, a viscosity. However, geodynamicists do not assign these values randomly. Although fictitious, once this entity is introduced into the numerical model, it has effects on the rest of the computational model and on the computing infrastructure that is required. The computer is programmed to solve the differential equations for each of the grid cells, including the cells representing the “sticky air” buffer. Adding grid cells to the model domain means increasing the number of calculations and *a fortiori* the time required to “run” the model and to obtain results. To optimise the computational efficiency of their model, geodynamicists seek to reduce the thickness of this fictitious layer, in the aim to reduce the number of grid cells on which they have to operate calculations. However, the thinner this layer and the more the boundary of the Earth’s crust and the boundary of the modelled domain merge — the more it resists the deformations of the Earth’s surface and acts on the latter by shearing it. This is precisely what geodynamicists seek to avoid, as they consider that this fictitious layer should not act on the surface. In short, in the words employed in one of the most cited research on this technique, this layer should not be “felt” (Crameri *et al.*, 2012, p. 39).

35 There is one fluid at the interface with the crust that is indeed not “felt” in the natural Earth system: air[7]. The geodynamicists whose work we report on try hence to make the properties of the fictitious layer resemble that of air, by assigning a density close to zero to it. However, another property of air is not suitable for their modelling purposes; air’s viscosity is very low compared to that of the adjacent crust. Numerical methods do not tolerate such a large difference, an abrupt jump in values from one grid cell to another. Taking into account this behaviour of numerical methods, geodynamicists strongly overestimate the viscosity of air. In their study, Crameri *et al* (2012) use a viscosity of between $10^{18}$ and $10^{20}$ Pascal*seconds (Pa*s), almost a hundred thousand quintillion times greater than that of air. Describing this air with the adjective “sticky” may therefore seem like an understatement. In fact, the only property this layer still has of air is its density; in terms of viscosity, it resembles the partially melted rock of the upper mantle.

36 Including a component that does not represent an element of the observed system — and even goes against our physical understanding of the world — is in itself hardly an exception in numerical modelling. Winsberg noted the presence of such elements “*that are different in kind from ordinary idealizations, approximations, and simplifications*” (2010, p. 87), which he refers to as fictions. The silogen atoms he analyses in nanomechanics, the artificial viscosity applied in shock wave modelling in fluid dynamics (Winsberg, 2006), the “Arakawa operator” studied by Lenhard (2007) and the contamination rate of the particle beam in the study of the “K+ - deuterium interactions at 3 GeV/c” experiment in high energy physics (Thill, 1973) share with the “sticky air” the characteristic of being introduced into numerical models to improve the overall representational power of the latter. As formulated by Winsberg, “*we are deliberately getting things wrong locally so that we get things right globally*” (2010, p. 92). The elements we provided in the previous sections allow us to circumscribe the “local” sketched in

Winsberg’s previous quote and to locate it. It is at the upper limit of the model domain — at this place of friction between the willingness to set things in motion (allowing the models to unfold towards new research questions) and modelling trajectories based on a total immobility of the model grid — that the “sticky air” emerges in order to deal with these antagonisms.

37 As we have observed in several interviews and in our informal conversations in our practice, modellers in the Earth and environmental sciences often have an ambivalent relationship with these modelling tricks. On the one hand, they consider these tricks to be necessary to negotiate with the computer infrastructure and these are therefore widely used and shared. On the other hand, these tricks seem to be a source of embarrassment when presenting their work, as if the evocation of such practices was likely to discredit the model results in the eyes of their conversation partners or readers. The next sections will therefore focus precisely on what geodynamicists do with the fiction of the “sticky air” in order to share it, communicate about it and tame its impact on the rest of their model.

## The “sticky air” layer, a research subject in its own right

38 While the trick of superimposing an extra layer on the Earth’s crust has been known in geodynamics at least since Matsumoto and Tomoda (1983), the term “sticky air” seems to have made its first appearance in the scientific literature in an article by Schmeling *et al.* in 2008. The authors use it alongside other descriptions such as “*soft surface layer*” or “*artificial layer*”. By describing it as a layer of soft material, they refer implicitly to its viscosity. By describing it as a layer of air, they refer implicitly to its density. It is therefore not surprising that the authors oscillate between these two names, each of which offers an analogy for one of the properties of this layer. The term “artificial layer”, on the other hand, reminds us of the non-existence of this element in the conceptual model of the Earth sciences.

39 A few years after Schmeling *et al.*, Quinquis, Buiter and Ellis (2011) used the term “sticky air” extensively, even going so far as to speak of an “air” layer. Here, only the inverted commas remind us of the singularity of this air, one hundred thousand quintillion times more viscous than the gas mixture we breathe. However, it is the article by Crameri *et al* (2012) that seems to have marked a definitive turning point in the use of the term — and in the use of the technique itself. For the first time, the “sticky air method” appeared in the title of a scientific article. The authors, most of whom are affiliated with the Institute of Geophysics at ETH Zurich (see above), attempt to evaluate the “sticky air” technique and determine the conditions for its use. They do this not only theoretically — by analysing the physical equations involved — but also by comparing the results obtained by integrating a layer of “sticky air” with those of models using other methods (a vertical deformation of the grid, among others). The study results in an equation which, according to the authors, allows the determination of “*suitable*” ranges of values for the viscosity, thickness and velocity of the “sticky air” layer.

40 Formerly a discreetly-used modelling trick — almost hidden in most of the previous articles and still deprived of a stabilised name — the “sticky air” is thus suddenly propelled to the rank of a research object. Its agency is exhibited and evaluated. The research questions addressed by the article no longer concern the natural phenomena

that the “sticky air” contributes to study, but the actions of this object and its interactions with the rest of the computational model. While it was an object *serving* research, the “sticky air” becomes an object *generating* research questions internal to modelling, on its own functioning and behaviour. It thus possesses the characteristics that the anthropologist Matt Spencer — taking up the work of historian of science Hans-Jörg Rheinberger — attributes to “methodological epistemic objects” in the computational sciences (Spencer, 2019). The evolution marked by the “sticky air” is far from being an isolated case in numerical methods. As soon as modellers consider that these methods can act — and not only in the way they wish them to — their behaviour in different situations is the subject of analyses. In an interview in January 2022, one of the co-authors of the Crameri *et al.* (2012) article was amused in retrospect by the fact that the study had only been carried out after the “*empirical use*” of the “sticky air” method. However, it is probably precisely the rapid spread of the “sticky air” method in the geodynamic community and the issues at stake — the opening of existing models to the study of the movements of Earth’s surface — that explain why the behaviour and properties of the “sticky air” were deemed sufficiently worthy of interest to set up such a large-scale study and to publish it. Ten researchers were involved, including several of the leading names in European geodynamics. They were running six different models for the purpose of the study. As each model has its own network of users with different approaches and modelling trajectories, the authors’ evaluation of the “sticky air” method may appear to be global; this multi-model comparison contributed to the credibility of the method for a wide audience. The article, which appeared in a well-known geophysical journal, seems to have become a must-have citation for any research that includes the “sticky air” method. It even replaces the description of the technique and of its functioning in many subsequent papers[8], as if the exhibition of the trick in the Crameri *et al.* (2012) paper would enable to close the black box.

## Giving credibility by referring to air

41 The study by Fabio Crameri and his colleagues certainly contributed to the credibility of the “sticky air” method through the status given to the technique, the involvement of different models manipulated by distinct collectives and the participation of researchers with authority in the discipline. We argue, however, that its stabilised name (“sticky air”, rather than the formerly used “soft surface layer” or “artificial layer”) also contributes to this credibility. The fact that this naming prevailed over the early competing descriptions seems to be due to the attempts to make sense of this component within the conceptual model. The “sticky air” layer is a trick of the computational model, of the numerical treatment of the system under study. It has a role and a justification within this computational model, but it has none in the conceptual model. As soon as it is qualified as air, however, it becomes also charged with meaning in the conceptual model. The Earth’s crust is indeed topped with air! Including a portion of the atmosphere in the model’s “box” does not seem that far-fetched. Adding a layer of several tens of kilometres of extremely viscous solid material on top of the Earth’s crust, on the other hand, is more likely to raise questions for readers of geodynamics: there is nothing like it in the natural system we know. By referring to the buffer layer as “air”, geodynamicists emphasise the similarity with the conceptual model and stress on the glass being half-full. Once transformed into an adjective, the difference is relegated to the background and to the simple function of an

attribute: this air is sticky. This adjective is from then on likely to be merely suggested (notably through inverted commas — see the quotation from Quinquis, Buiter & Ellis, 2011, above), or even deleted for the sake of brevity in the names of variables:

> The upper half of the model is filled with a thick layer of “sticky air” with a density $\rho_{\text{air}}$ and a viscosity of $\eta_{\text{air}}$ to simulate a free surface (Fuchs, Koyi & Schmeling, 2015, p. 82)

42 The confusion between this “sticky air” and the air of our natural system is reminiscent of the confusion observed by anthropologist Myanna Lahsen (2005) between modelled and observed elements in the oral communication of modellers in climate sciences. The blurring (whether unintentional or not) between the two signifieds, the relegation of this particular viscosity to an attribute (“sticky”) that is hardly described at all, also seems to contribute to consolidating the credibility of the method, as does the use of the noun “air” referring to an element that actually surrounds the Earth’s crust. We do not see this confusion as a proven deception, intended to mislead readers in geodynamics about the nature of this layer. Rather, it seems to be an attempt to mitigate the fictitious nature of this element, out of the apparently widespread fear in the Earth and environmental sciences that the evocation of such a fiction might diminish the representational power of the models. The methodology sections of geodynamic modelling articles thus act as grey boxes, displaying at times their components to allow readers to grasp their interlinking, to evaluate the method and to re-use it, while rendering some of their properties invisible at other times so as not to breach an edifice intended to resist the criticism of reviewers and peers. We shall note that the singularity of the “sticky air” — its lack of physical significance and its extreme viscosity compared to air — is hardly discussed in the geodynamic literature. A paper by Duretz, May and Yamato (2016), presenting an alternative technique, appears to be the only one explicitly noting the fictional nature of the “sticky air”. However, this fictionality is only pinpointed as a limitation at the conclusion of the paper, in a final enumeration of the advantages of their method which — unlike the “sticky air” method — *“does not require arbitrary choices to be made for material properties associated with a fictitious fluid”*. The background of two of the authors — co-authors of the “sticky air” study by Crameri *et al.* (2012) — and some of the remarks we collected during an interview nevertheless lead us to consider it a rhetorical statement, rather than a sign of an existing controversy.

## Representations of the fictional being

43 Numerical modelling in the Earth sciences is the subject of numerous scientific publications which take the form of articles. In their methodology, the authors usually describe the model used and its main equations, the values of the chosen parameters, the approximations that were made, as well as the spatial and temporal resolution. In contrast to other Earth science disciplines (such as hydrology, geomorphology, climatology or oceanography), geodynamicists add to their papers a visual representation of the model domain, composed of the different layers that are modelled. Since geodynamicists are interested precisely in the dynamic evolution of these layers, these initial diagrams are of high importance.

44 The use of the “sticky air method” is a trick among geodynamicists that places them in an unusual situation in this regard. As the “sticky air” layer is part of the model domain, geodynamicists give it a visual presence: a delimited surface, a colour code, a

legend. While the numerical existence of this entity is drowned in thousands of lines of computer code and only appears to those who can read them, its visual existence is manifest; the “sticky air” layer is displayed in the open, alongside layers of material (continental crust, sediments, mantle, for example) which behaviour forms the central subject of the published articles. However, it remains discreet. The authors most often attribute white to it, while the other layers are abundantly coloured. Being white on the white paper, or white on the electronic document with a white background, the “sticky air” layer is almost invisible: it is only revealed to readers by the space it leaves — by its very presence — between the upper limit of the model and the surface of the Earth.

Figure 3 : Visual representation of the sticky air layer

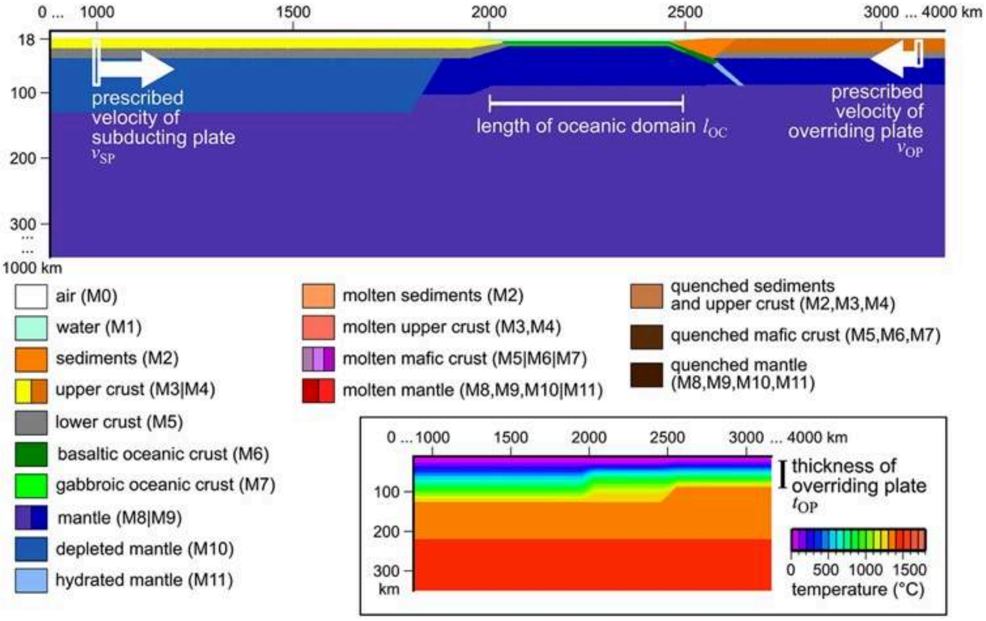


Illustration appearing in an article by Maierová, Schulmann and Gerya (2018) showing the initial distribution of “materials” in the model domain and the temperature field. Using this model, the researchers aim to simulate the transformations of the continental crust during a collision between two tectonic plates.

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45 Figure 3 displays one of these representations. A thin white stripe overlies the rest of the model’s domain. The legend is of particular interest here. The noun used alone (air) again suggests that the authors really wanted to include the first eighteen kilometres of the atmosphere in their conceptual model. We know that this is not the case, as the atmosphere plays no role. In their numbering, the authors abbreviate it by the code M0; air is material (M) zero. This numbering reflects the ambiguous position of the sticky air layer, a material included in the model domain and therefore represented, but a material of another type — one that should not exert any influence, that should not count, just as it does not count in the conceptual model.

## The “drunken sailor instability”: an unwanted effect of the fictional entity calling for further modelling tricks

46 The “sticky air” layer has however much more impact than the analogies to air might suggest. Firstly, by the simple fact that it occupies additional grid cells in the model, it increases the computational cost of the modelling (see above). Secondly, it impacts in an even more direct way the rest of the model, as we will see below.

47 The “sticky air” method allows geodynamicists to model the Earth’s crust as a free surface, which can be deformed, but which can also be unstable. Indeed, free surfaces tend to give rise to an anomaly within numerical models known as “*drunken sailor instability*” (Kaus *et al.*, 2010; Gerya, 2019). The flow velocity of the rocks then begins to change direction at each time interval (Kaus *et al.*, 2010), repeatedly lifting and lowering the Earth’s crust. This problem is the flip side of the method’s success; it is because geodynamicists are able to approximate a free surface that they are faced with this surprisingly oscillating crust, disrupting their results.

48 The path taken by modellers to shape the “sticky air” trick was already quite winding; however, a few more turns are still needed to overcome this anomaly. Various workarounds, including stabilisation algorithms (Duretz *et al.*, 2011; Kaus *et al.*, 2010) and time integration schemes (Furuichi & May, 2015) have been developed and integrated into the models. These new numerical tricks are also completely absent from the conceptual model of the natural system studied. They “only” correct the undesirable effects of the previously introduced fictitious entity, the “sticky air”. Nevertheless, they have their own existence in the geoscientific literature. Their effects on the equations governing the model, on the model results and on the use of (numerical) resources are analysed, evaluated and discussed.

49 The large number of scientific publications generated by the study of numerical methods, their repeated presentation and discussion at conferences, attest to their importance for the geodynamic community. These are not mere technical details of a well-oiled process. On the contrary, we agree with anthropologist Matt Spencer (2019) on the fact that numerical methods are research objects that engage researchers in the disciplines which develop and employ them. These methods, tricks and fictitious entities animate research communities for whom they constitute epistemic objects, in the same way as the phenomena they ultimately allow to explore.

# Conclusion

50 Following both locked-in and unfolding modelling trajectories, geodynamicists and the beings they produce and mobilise trace winding paths, overcoming successive obstacles by means of mathematical, numerical and conceptual sleights of hand, which are objects of discussion and the result of consensual elaboration. The first lesson of this case study lies precisely in the non-linearity of this path, contrary to what the unidirectional arrows of the operation diagrams (see fig. 1) suggest about the modelling activity. The transition from a quantitative description of the processes at work (the conceptual model) to a mathematical model, and then to an executable code (the computational model) engages modellers in collective explorations, negotiations and trade-off constructions — between the sometimes locked-in modelling trajectories on

which they are jointly evolving, the desires to unfold the model strategically towards new goals, their understanding of the processes, the material and economic constraints of their infrastructure, and the compatibility of the results with the conceptual model which they are revising. These dynamics vary according to the modelling situation. They are not a series of transposable or automatable operations. Sociologist Mikaela Sundberg summarises the transition to an executable code by the term “translation” (2010, p. 273), which should be understood in the sense of actor-network theory as the displacement, transformation and betrayal of the entities in presence — in this case the conceptual model and the computational model — which is the basis for their equivalence (Callon, 1986) and their re-creation (Eco, 2007). In the course of the transformations of the mathematical model into a computational model, the modelled Earth system is in fact considerably modified. It has not only been cut into a finite number of grid cells in order to enable the approximation of the solutions of the differential partial equations used. The processes taking place at a scale inferior to that of the grid cells did not only have to be simplified. Like the $(re)^n$-presentation process described by Bruno Latour (1993), the Earth system has also been enriched — in this case with a new component. A layer of several tens of kilometres of a material unknown to our perceptible world, with both the density of air and a viscosity close to that of the Earth’s mantle, has covered the surface of our planet.

51 This numerical trick does not remain confined within the computational domain. We have seen how some authors in geodynamics navigate it backwards, through a semantic shift, to the conceptual model from which this hybrid could have emerged. In fact, numerical methods need to be put into words to be presented, analysed and shared with peers. The analysis of scientific articles enabled us to raise one of the issues linked to putting these pieces of computer code into words: that of an additional credibility sought through naming and visual representation, which would deserve to be captured by ethnographic studies. Within the scientific articles analysed, the ongoing confusion between the two signifiers of air (sticky or not) makes the borders between conceptual, mathematical and computational models disappear. Isn’t this “air” — which is white (and therefore invisible on the sheet of paper), this “zero” material (and hence not counting) — the air-without-inverted-commas? In all its fictional aspects (Winsberg, 2010), the numerical trick fades away; because of the choice of words and its visual representation, all what seems to remain is the gaseous mixture which presence we would not dare to put into question. We must remember its genesis, the path punctuated by multiple negotiations and explorations in contact with the trajectories and limits of the model, to avoid the deception and to see this “sticky air” as an element created solely for the needs of the computational model.

52 This observation is not without consequences for our approach to numerical modelling. Firstly, it demonstrates — we paraphrase Lenhard (2007, p. 87) here with our own terminology — that the computational model is partially disengaged from the conceptual and mathematical models. In fact, an element emerges that is absent from the conceptual and mathematical models, and neither derived nor approximated from the latter. The passage from the mathematical model to the computational model executable on the computer is thus the result of a new creation, a full-fledged re-modelling, negotiated with the particular constraints of numerical processing. Seeing this stage of “making executable” as a creative process, as Winsberg (2010) and Spencer (2012b) do, stands in contrast to the technological determinism often suggested by

science studies work on modelling, due to the lack of investigation of this stage of modelling. Our study of the “sticky air method” highlighted the existence of choices, of co-existing alternative pathways for the implementation of the same process. For the geodynamicists we met, the “sticky air method” is thus only one possible route among others. The fact that many of them chose it cannot be explained solely by a comparison of the computational cost of the different methods. The weight of path dependencies, of accumulated individual and disciplinary experience, of collaborations, would deserve to be more widely studied through field work. This would allow a better understanding of the emergence and stabilisation of numerical modelling practices, which feed an ever more considerable part of scientific research in the Earth sciences.

53 If there are creative and negotiated practices at play, if the development and choice of a numerical method is of such great importance within the disciplines employing them, it is indeed surprising that the study of computational models has so far been mainly the preserve of philosophers of science[9]. Spencer (2012b and 2019) and his ethnographic work on models in computational science is a notable exception to this, though hitherto ignored by the various approaches of science studies to geoscientific modelling. The “sticky air method”, dissociating the boundaries of the model domain and that of the crust and the mantle, finally enjoins us to straddle other boundaries: those demarcating on the one hand the territories of STS work on Earth science modelling and on the other hand, the studies on computational sciences — even though they are undeniably intertwined by the very nature of the numerical instrument.

*We warmly thank Thibault Duretz for the exchanges around this article at various stages of its writing, as well as the other geodynamicists we contacted and who spoke with contagious enthusiasm about their research. An earlier version of this article was the subject of a workshop at the University of Lausanne's Science and Technology Studies Laboratory (STS Lab) and benefited from feedback from the editorial board of the journal Terrains & Travaux. Finally, we would like to thank the four anonymous reviewers of the RAC for their valuable comments, which enabled us to improve the current version.*

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## NOTES

**1.** In her practice, the co-author of this article observed that these sketches could for example take the form of very simple sketches of the system to be modelled. They could be topped with a grid pattern representing the “grid” of the model and with bits of equations (or computer instructions) linked to certain elements of the grid.

**2.** The result of the action of the mantle on the Earth’s crust is referred to as “dynamic topography”. The adjective “dynamic” is used to distinguish this topography from the relief generated by interactions between tectonic plates (by sliding, spreading or subduction). Dynamic topography has a relatively small amplitude: of the order of 1000 m (positive or negative) height difference over a distance of several hundred or even thousands of kilometres (Braun, 2010).

**3.** Historically, some modellers simply calculated the movements of the Earth’s crust without explicitly simulating them. Geodynamicists modelled the forces exerted by the mantle on the crust and tried to determine the resulting rise or fall by calculation. In these models, the Earth's crust was not set in motion. Nevertheless, this technique, which presupposes many approximations (Zhong *et al.* , 1996), seems to be considered outdated in the current geodynamic literature.

**4.** Geodynamicists use numerical methods to approximate the results of the partial differential equations they use. There are three such methods: the 'finite difference' method, the 'finite element' method and the 'finite volume' method, which is still very rarely used in geodynamics.

**5.** *A posteriori*, the choice of one of the two numerical methods is frequently justified in the geodynamic literature by advantages in terms of ease of implementation, computational efficiency or compatibility with research objectives.

**6.** These are mainly techniques involving the insertion of *markers*, particles representing the position of the Earth’s surface that can be set in motion within a fixed grid (see Gerya, 2019).

**7.** This is also the case for water; some geodynamicists apply the density of water to their 'sticky air' layer, depending on the situation being modelled.

**8.** Balazs *et al* (2021) write as a unique description that “a 20 km layer of 'sticky air' is defined at the top of the model (Crameri *et al.* , 2012)”. This example is representative of a large number of publications.

**9.** In addition to the above-mentioned authors, we should mention Gramelsberger (2011) and her work on the impact of the changes brought about by computer coding on the representational power of models.

# ABSTRACTS

Numerical models contribute to a substantial part of research conducted in Earth sciences. To be executed on a computer, the mathematical representations they depict are transformed into a computer program. The present article aims at following this transformation and at questioning the implications of rendering a representation computationally executable. It uses to this end a case study of the so-called “sticky air” numerical method employed in geodynamics, which consists of putting a layer of a hybrid material — a hundred thousand quintillion ($10^{23}$) times more viscous than air — on top of the Earth crust. Far from being only a marginal and automatic step in the modelling process, the constitution of an executable computer code is the result of a profoundly creative and negotiated practice.

Les modèles numériques nourrissent une part substantielle de la recherche en sciences de la Terre. Afin de pouvoir être exécutées sur ordinateur, les représentations mathématiques des processus qu’ils décrivent sont transformées en programme informatique. L’article se propose de suivre ce passage et d’interroger ce qu’implique le fait de rendre exécutable, au moyen de l’étude d’une méthode numérique employée en géodynamique et dite de « l’air collant ». Cette dernière consiste à surmonter la croûte terrestre d’un matériau hybride d’une viscosité cent mille milliards de milliards ($10^{23}$) de fois supérieure à l’air et atteste des transformations requises afin de composer avec les contraintes du traitement numérique. Loin de n’être qu’une étape marginale et automatique du processus de modélisation, l’élaboration d’un code exécutable relève ainsi de pratiques profondément créatives et négociées.

Los modelos numéricos constituyen una parte sustancial de la investigación en ciencias de la tierra. Para ser ejecutadas en una computadora, las representaciones matemáticas de los procesos que describen son transformados en programas informáticos. Este artículo pretende seguir este proceso y examinar lo que supone el hacer ejecutable un método numérico utilizado en geodinámica, conocido como «aire pegajoso». Este método consiste en superar la corteza terrestre con un material híbrido cuya viscosidad es cien mil trillones ($10^{23}$) veces mayor que la del aire, y da fe de las transformaciones necesarias para hacer frente a las limitaciones del procesamiento digital. Lejos de ser un paso marginal y automático en el proceso de modelización, el desarrollo de código ejecutable es, por tanto, una práctica profundamente creativa y negociada.

Numerische Modelle sind ein wesentlicher Bestandteil der Forschung in den Geowissenschaften. Um auf einem Computer ausgeführt werden zu können, werden die mathematischen Darstellungen der Prozesse, die sie beschreiben, in ein Computerprogramm umgewandelt. Der Artikel verfolgt diesen Prozess und untersucht, was es bedeutet, etwas ausführbar zu machen. Dafür untersucht er eine numerische Methode der Geodynamik, die sogenannte Methode der „klebrigen Luft“ (sticky air method). Bei dieser Methode wird die Erdkruste mit einem Hybridmaterial überzogen, dessen Viskosität hundert Trillionen ($10^{23}$) Mal höher ist als die von Luft; sie veranschaulicht die Transformationen, die notwendig sind, um mit den Einschränkungen der numerischen Verarbeitung zurechtzukommen. Die Entwicklung eines ausführbaren Codes ist also keineswegs nur eine marginale und automatische Phase des Modellierungsprozesses, sondern ein zutiefst kreatives und ausgehandeltes Verfahren.

## INDEX

**Mots-clés:** modélisation, méthode numérique, géodynamique, sciences de la Terre
**Palabras claves:** modelización, método numérico, geodinámica, ciencias de la tierra
**Keywords:** modelling, numerical method, geodynamics, Earth sciences
**Schlüsselwörter:** Modellierung, Numerische Methode, Geodynamik, Geowissenschaften

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