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Project-oriented agency and regeneration in socio-technical transition: Insights from the case of numerical weather prediction (1978–2015)

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Abstract

This paper analyzes the unfolding of socio-technical transition (STT) using the multi-level perspective (MLP) framework. It relies on an in-depth case study of the "quiet revolution" of numerical weather prediction. The study reveals how key actors targeted the reverse salient of data assimilation and thereby facilitated the transition toward a new "variational" regime. In so doing, the paper makes three contributions to the STT literature: 1) it identifies a new type of transition pathway, "regeneration," in which the regime transforms itself from within, despite the lack of changes in landscape pressure, to overcome internal tensions; 2) it showcases "project-oriented agency" as the central mechanism of this transition, which allows the actors to join forces and cooperate to counteract the reverse salient; and 3) it proposes a process model of project-oriented agency that accounts for the role of the reverse salient in the regeneration pathway.

Keywords: socio-technical transition, regeneration, multi-level perspective, reverse salient, project-oriented agency, data assimilation, weather forecasting.

1. Introduction

Socio-technical transition (STT) constitutes an important topic in innovation studies. For more than two decades, the multi-level perspective (MLP) has contributed profoundly to our understanding of STT by integrating a wide body of literature to address STTs' nature and underlying processes (Geels, 2002). Prior research within the MLP tradition has identified a number of technical, social, legal, and institutional factors that play central roles in enabling STT, and demonstrated how these factors vary across different transition pathways (Geels and Schot, 2007; Geels et al., 2016). In particular, MLP research has provided a thorough understanding of the macro-oriented developments that enable STT, and shown how landscape pressure enables and sometimes hinders STT, along with the role played by niches in shielding and providing opportunities for the emergence of technological breakthroughs.

Initially, most studies within the MLP tradition focused on long-term and macro historical case studies, paying scant attention to agents and agency—i.e., what individual actors and/or organizations do, and their capacity to act and enable intended effects (e.g. Smith et al., 2005). In contrast, more recent MLP work has favored an explicit focus on agency to better address what actors can (and cannot) do to enable STT. From that end, a novel and promising stream of research has emerged within the MLP tradition that centers on the role and variations of agency in different transition pathways. This suggests a stronger and more explicit focus on the microfoundations of STT, favoring an analysis of shorter and more intense periods of technological change.

So far, MLP research has addressed the agency problem in three ways. First, Geels (2010) demonstrates that, theoretically speaking, MLP research accommodates different ontologies of agency (rational choice, structuralism, etc.). Second, research on Strategic Niche Management (SNM) has analyzed the role of projects, or sequences of projects, at the niche level to nurture radical innovation in sheltered places (Raven, 2005; Schot and Geels, 2008; Raven and Geels, 2010). Third, Geels et al. (2016) analyze how transition pathways are enacted through various agency mechanisms at the regime and/or niche level (e.g., ambidexterity of incumbent firms in the regime). Along the same lines, Turnheim and Geels (2019) present an analysis of the role of "landmark projects" in infra-system transitions to grasp the role that particular projects play in enabling STT.

However, a central problem in STT is associated with the formation of agency itself, which is seldom addressed in extant MLP research. Prior research on agency in STT instead typically considers either how the context influences the search process (i.e., guided search in Turnheim and Geels, 2019), or the impact of the project on the actual transition (e.g., technical viability and use exemplification), with less emphasis on the emergence of projects that enable transition in terms of their types and timings. This is perhaps especially important and intriguing in the context of large technical systems (LTS), where several technologies are interdependent, and many actors need to collaborate to establish agency for generating system-wide advances (Hughes, 1987).

For instance, we know from the groundbreaking work of Thomas Hughes (1983; 1986) that LTS evolution is uneven and faces severe challenges in terms of identifying and overcoming problems associated with reverse salients—i.e. particular components or technologies that hinder an LTS's development and improvements. According to Hughes (1983), to make substantial system-wide advances, the reverse salient must be identified and addressed, which is far from a trivial issue in contexts of intensifying complexity and rapid technological change. Interestingly though, from an agency point of view, the reverse salient constitutes both a fundamental obstacle and an opportunity: its successful identification could be a factor that contributes to establishing agency, and would thus allow for further social and technical transition.

To address this issue, our paper presents the illuminating case of the "quiet revolution" (Bauer et al., 2015) of numerical weather prediction (NWP). We direct empirical attention to the consequences of introducing satellites to earth observation systems, which led to extensive changes in NWP. Indeed, it took almost 30 years for satellite data to improve forecasting performance. The transition required a radical transformation in data assimilation methods—from the optimal interpolation (OI) regime to the new 4D-VAR regime. As we shall demonstrate, counteracting the associated reverse salient called not only for conceptual breakthroughs in the mathematics of data assimilation, but also a forceful collective endeavor: the IFS/ARPEGE project, established by the European Centre for Medium-Range Weather Forecast (ECMWF) in collaboration with the French weather service Météo-France.

The initiation of this project indicated both a common view of the reverse salient (concerning data assimilation) and a targeted approach to solving it. That view ultimately led to the diffusion of the 4D-VAR method to weather forecasting centers worldwide (Bauer et al., 2015)—a diffusion that substantially improved both data processing capability and the quality of forecasts, and is the main reason why satellite data now play such a key role in NWP (Joo et al., 2013; Saunders, 2021).

Therefore, the aim of this paper is to enhance our understanding of the *nature* and *process dynamic* of agency in such STT settings. The following research questions guided our research: (1) What are the characteristics of this transition pathway, and how does it correspond to existing typologies of transition pathways? (2) What are the elements of agency in this type of transition pathway, and how does agency emerge in such type of pathway? We use in-depth findings from the case of NWP to answer these questions and make three contributions that enhance our understanding of agency in this kind of transition pathway.

First, our case reveals a novel type of transition that we refer to as *regeneration*. Our study indicates that the quiet revolution of NWP occurred without significant changes in landscape pressures—a central force in the extant MLP typology. On the contrary, in regeneration, the central mechanism of transition originates from *within* the regime, and attempts to overcome the internal tensions that appear along with new technologies. Moreover, our study shows that the creative accumulation of new competencies by incumbent actors (Geels, 2006; Bergek et al., 2014) was activated by a project—the IFS-ARPEGE project—to implement endogenously generated radical changes: 4D-VAR data assimilation. In that regard, we argue that the regeneration pathway constitutes a potentially novel type of transition pathway that could mirror transitions in other contexts where problems relate to how internal tensions are established and overcome, and how incumbent actors build new competencies and collaborations. The notion of regeneration thus enriches current research on STT pathways (Geels et al., 2016) and enhances our understanding of transition in contexts where reverse salients play a central role.

Our second contribution pinpoints a particular type of agency operating in the regeneration pathway: *project-oriented agency*. Project-oriented agency focuses on collective action that targets specific critical problems (such as the reverse salient) to enable transition. Thus, and in line with more recent work on agency in innovation (e.g., Berggren et al., 2015), we underscore the importance of projects for driving such transitions in high-tech and complex industries (Dougherty, 2016), and thereby enhance our understanding of how actors identify and act on reverse salients (Hughes, 1998). We highlight that addressing the meso (project) level not only enables a better grasp of collective agency in high-tech industries, it also demonstrates the strong connections between management/organization and STT that have been underscored—though little scrutinized empirically—by scholars within the MLP tradition (see, e.g., Geels, 2011). Based on our empirical study, we identify four core elements of project-oriented agency (goal agreement, knowledge/resource mobilization, temporary trading zone, and impetus) that together provide an understanding of the *nature* of project-oriented agency.

Third, responding to calls for a better understanding of how agency is established in STT, we center on how project-oriented agency emerges, and pinpoint how the four elements of project-oriented agency work together over time to enable STT in an industry that is highly connected on a global level. Thereby, our analysis adds granularity to earlier studies of agency in transition that have typically focused on local contexts (see, e.g., Turnheim and Geels, 2019). In sum, our analysis of the emergence of project-oriented agency provides us with a better understanding of the *process dynamic* of agency in the regeneration pathway.

The remainder of our paper proceeds as follows. Section 2 discusses the theoretical background with a focus on STT pathways and the role of agency. Then, in Section 3, we introduce the context of our research and describe our data collection. Section 4 presents our findings, and in Section 5 we discuss their theoretical and practical contributions and implications. Section 6 concludes with a brief summary and some suggestions for future research.

2. Agency in socio-technical transition

Research on STT has expanded considerably over the last two decades, with a number of groundbreaking contributions that have enhanced our understanding of both the macro-oriented occurrences and the more micro-oriented activities that enable STT. MLP researchers have studied a wide range of empirical contexts, from the transition from horse-drawn carriages to automobiles (Geels, 2005) and the rise of tramways in France (Turnheim and Geels, 2019) to the development of renewable and low-carbon energy sources (Geels and Raven, 2006; 2010, Geels et al., 2016).

The central concept of the MLP is the socio-technical regime, defined by Rip and Kemp (1998) as “the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artifacts and persons, ways of defining problems—all of them embedded in institutions and infrastructures” (p. 338). The socio-technical regime extends the classical concepts of technological paradigm (Dosi, 1988) and dominant design (Abernathy and Utterback, 1978) to also take into account the rules and institutions that support a particular technology. The regime explains the stability of existing technologies and, therefore, the difficulty of radical innovation. In order to explain the emergence of radical innovation and the transition from one regime to another, the MLP addresses how the regime, the "socio-technical landscape," and "niche innovations" interact to generate (or impede) a transition. Indeed, in the MLP framework, following Giddens' structuration theory (1984), the niche, regime and landscape provide structures that are dual in nature: both constraining and enabling action (Geels, 2011). However, as pointed by Geels and Schot (2007, p. 403), "an important difference between niches and regimes is that the constraining influence is much stronger for the latter" (p. 403). Indeed, in the regime, rules, cognitive routines, as well as, networks of relations, are stable and ingrained in actors' practices, thus delimiting the range of choices and innovations to more incremental ones. On the contrary, niches offer greater freedom for actors to experiment with radical changes, whereas the landscape provides the stabilizing context which is outside the control of Individual actors, at least In the short term.

There are, given the focus of the present paper, three primary benefits of the MLP framework. First, it integrates a wide body of literature in innovation studies that adheres to an evolutionary perspective. Second, by relying on the concept of socio-technical regime, it encompasses technical, social, legal, and institutional factors (see also Hargadon and Douglas, 2001) and thereby enables a richer and multi-dimensional understanding of STT. Third, the distinction between the niche and landscape levels leads to an instrumental typology of transition pathways (Geels and Schot, 2007; Geels et al., 2016) based on the different dynamics involving three levels: landscape, regime, and niche.

Indeed, whereas in its early days the MLP clearly favored a bottom-up approach that saw innovation principally emerging from niches, and where strategic niche management played a key role (Hoogma et al., 2002; Raven, 2005), more recent works have emphasized the complex interplay between the three levels. To grasp how this interplay operates in different settings, Geels and Schot (2007) identified four transition pathways depending on the timing of the interactions between landscape pressure and niche innovations (are they mature enough?) and the nature of these interactions (are they "symbiotic" or "competitive"—i.e., do they reinforce or disrupt the regime?), and how they impact transition (see Table 1).

Table 1: Typology of transition pathways

Type of transition pathway	Definition
Technological substitution	This pathway is principally based on disruptive niche innovations that are sufficiently developed when landscape pressure arises.
Transformation	This pathway is led by landscape pressure that fuels incumbent actors to gradually adjust the regime, when niche innovations are not sufficiently developed.
Reconfiguration	This pathway is based on symbiotic niche innovations that are incorporated into the regime to solve local problems and trigger further (architectural) adjustments under landscape pressure.
De-alignment/realignment	This pathway is enabled by major landscape pressure that destabilizes the regime when niche innovations are insufficiently developed; the prolonged coexistence of niche innovations is followed by the re-creation of a new regime around one of them.

Source: Based on Geels and Schot (2007) and Geels et al. (2016, p. 896). Geels et al. (2016) discuss and complete this typology, in particular by focusing on the agency processes underlying the enactment of these pathways.

Despite its benefits and widespread diffusion, the MLP framework is not without criticism. In particular, Smith et al. (2005) and Genus and Cole (2008) argue that the long-term and macro-historical case studies typical of much research on STT only marginally grasp the role of agency and the actual doings of the actors leading a transition process. Geels and Schot (2007) acknowledge that agency "does not always come through strongly in stylized case studies and figures" (p. 414). This limitation, the authors say, is probably due to the fundamental nature of much research on STT, which has sought to develop a "global model that maps the entire transition process" (p. 414), to the detriment of a thorough analysis of the most important processes, in particular agency (Sorrell, 2018).

However, in recent years, the MLP literature has emphasized the significance of agency in furthering the understanding of STT (Köhler et al., 2019). Several studies identify the type of agency that underpins STT and have pointed out the differences in terms of agency across different settings (e.g., Geels and Schot, 2007). First, Geels (2010) explains how the MLP framework accommodates different ontologies of agency (rational choice, structuralism, etc.). Moreover, Geels et al. (2016) refined the original typology and demonstrated how agency leads to the enactment of different pathways from one regime to another.

A second approach, Strategic Niche Management (SNM), originally developed by Kemp et al. (1998), Raven (2005), and Schot and Geels (2008), recognizes the role played by projects and sequences of projects, especially at the niche level. Various kinds of "strategic projects" may serve as "sheltered places" (see also Smith and Raven, 2012) to experiment with new technology (Raven and Geels, 2010) that “may gradually add up to an emerging field (niche) at the global level” (Schot and Geels, 2008, p. 543), which may, in turn, lead to a transition. For instance, Raven (2005) and Raven and Geels (2010) demonstrate the usefulness of this approach by exploring the sequence of (successful and unsuccessful) projects related to biogas development in the Netherlands and Denmark (see also Hoogma et al., 2002, for the case of sustainable transport).

Indeed, as argued by Geels et al. (2016), MLP research focuses on agency at the meso level. It explains “trajectories in terms of event-chains and rounds of moves and counter moves” (p. 898), not “by particular events or local projects by zooming-in on specific actors and (local) practices” (ibid.), which are supposed to be “less useful for the conceptualization of transition pathways which refer to more aggregate patterns over longer time periods” (ibid.). However, the MLP research fails to capture much of the granularity that the meso level brings to transition processes. This, we will argue, is particularly true for projects, which are mainly studied from afar. In particular, little attention is given to aspects of engineering and design work, such as the technical problems involved and how they are tackled by individuals and collectives to facilitate STT (e.g. Hargadon and Douglas, 2001, on Thomas Edison and electric lighting). This has been singled out as a significant shortcoming of extant MLP research. In a recent paper, Turnheim and Geels (2019) underline the role of landmark projects in infra-system transitions by focusing on the rise of tramways in France from 1971 to 2016. Such projects, they argue, have a catalytic effect on STT by exemplifying technical verification and use. Moreover, they state, “their design implications were systematically replicated in later projects” (p. 1425; see also Brown and Hendry, 2009). In the present paper, we continue along this line of inquiry into the role of landmark projects in STT pathways.

More precisely, we theorize that adopting the project as a central locus for analysis may constitute an integrative meso level, between actors and the regime, at which certain problems (in our case, problems of reverse salients in large technical systems) can be most appropriately addressed. We then incorporate agency by drawing on Dougherty’s (2016) analysis of the challenges to establishing agency across multiple actors in complex innovation settings. Dougherty singles out the project level as the central locus for understanding the emergence of complex innovation. She stresses the importance of projects to define and solve the underlying problem, as well as how difficult, yet critical, these tasks are in emergent, multi-actor innovation settings (see also Dune and Dougherty, 2016).

In this paper, we argue that the notion of project-oriented agency enables a better understanding of collective agency in STT, and demonstrates the need for a stronger connection between the management/organization studies and the STT literature (a connection called for by Geels, 2011). Against this background, we argue for an explicit focus on the emergence and historical contextualization of projects (Hughes, 1998; Engwall, 2003; Manning and Sydow, 2011) to unveil how projects trigger manifold changes in their environment that contribute decisively to STT. Elaborating further on collective agency in such exploratory settings, we zoom in on the nature and emergence of project-oriented agency as a means to overcome problems associated with reverse salients. This enables us to develop a process model of the role of projects in the regeneration pathway. As we will demonstrate, in such settings, the regime, in the absence of evident and strong landscape pressure, is renewed from within, and resolves its internal tensions through project-oriented agency in order to transform its creative accumulation of new knowledge and competencies (Bergek et al., 2013) into operations. In particular, we believe there are two issues that are essential for advancing our understanding of agency in STT.

The first concerns reverse salients as a particular kind of challenge for anyone exploring STT in a complex and rapidly developing industry. The reverse salient seems to represent a critical issue for establishing agency, since it obliges multiple actors in more complex innovation settings to agree on a plan for action. Hughes' (1983) classic study of electrification as a case of systemic technological change describes the shift from gas to electricity in detail. He highlights the significance of reverse salients: particular components (e.g., technologies, products, sub-systems) that hinder a system's evolution and broader-scale improvement. (e.g., high-resistance filament; see Hughes, 1983). Therefore, to make appreciable system-wide improvements and advances, the reverse salient must be identified and addressed.

Yet, identifying and understanding the nature of the reverse salient is far from straightforward, and acting on it often proves to be an even more difficult feat. As Hughes (1992) points out, defining a reverse salient as a central problem is itself "a major step toward a solution or invention, for it is well known that the ability to define an amorphous situation as a problem is often an anticipation of a solution" (p. 100). Therefore, the second issue addressed here is related to the formation of agency itself (its nature and process dynamic), which is needed to enable STT; so even when actors have identified a reverse salient, they must still identify the means by which necessary collective action can be facilitated.

3. Research context and methods

This research began in 2010, when one of the authors was studying innovation processes within the French national space agency (Centre National d'Études Spatiales; CNES) in the domain of earth observation. Today, earth observation satellites have a broad array of applications, ranging from the images that illustrate Google Earth to climate monitoring, operational oceanography, and weather forecasting (Whalen, 2007). In 2014, those advances led us to focus on the value and operational uses of space data—a recurring problem within the space industry (Courain, 1991; NRC, 2000; 2003). Toward that end, we examined the case of meteorology. Indeed, today, weather satellites provide nearly 80 percent of the data used in NWP systems. Yet, as our case study demonstrates, this dominance masks a long struggle to use satellite data in an effective way.

3.1. A brief introduction to numerical weather prediction and data assimilation

An NWP model cannot function properly without an immense amount of data—often more than a billion data points. Technically speaking, NWP is an "initial value problem", and so a minor mistake in assessing the initial conditions could have a major impact on forecast accuracy (Kalnay, 2003). In the initial stage of forecasting, *data assimilation*, the goal is to use "all the available information [balloons, ground stations, satellites, etc.] to produce the most accurate description possible of the state of the flow, together with the uncertainty resulting from uncertainties on the various sources of information" (Talagrand, 1997). The ultimate forecast builds on that foundation. This cycle is repeated at least twice per day. The first step is challenging because of the "non-trivial, actually chaotic, underlying dynamics" of the physical processes involved, and because there is so little time to perform the required calculations (Talagrand, 2014).

The problem of data assimilation in weather prediction cannot be fully grasped without knowing that there are many fewer observations than there are grid points in the model (approximately 1 observation per 100 grid points). This explains why meteorologists rely on complex mathematical methods that combine current observations and the preceding forecast to generate a "first guess." Until the early 1990s, the "operational analysis scheme of choice" was optimal interpolation (OI; see Kalnay, 2003, p. 150). In OI, the values at missing grid points are approximated from information available in the neighborhood of those grid points. Our study indicates that the STT took off when, in the 1980s, data assimilation became a reverse salient that hindered the performance of NWP.

3.2. Data collection and analysis

We took a process approach (Langley, 1999; Yin, 2003; Langley et al., 2013) and collected our main data from May 2014 to May 2015. We relied on the following sources of data:

1. The innovation history literature and the science and technology literature that address meteorology and space technology. Conway (2008) triggered our curiosity about the conflict in the U.S. between the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) concerning the use of satellite data in NWP. Courain (1991) presents a detailed study of the difficulty of using remote sensing data in weather prediction. Research by Krige (2000) and Edwards (2010) helped us understand the problem in greater depth. We also relied on U.S. National Research Council reports about the severe and decades-long problems with the operational use of space data (NRC, 2000; 2003).
2. The scientific literature on meteorology. Since our research generated a large amount of information and spanned several decades, the meteorology literature helped us better understand the problems at stake, and prepared us for interviewing the principal actors in the actual transition process. Moreover, this literature allowed us to crosscheck our interviews, track debates in the meteorological community, and verify and add nuance to the data collected from our interviews.
3. Interviews. The interviews covered the process of transition and change in as much detail as possible (see the appendix on data sources). They were recorded and transcribed verbatim. We also conducted several shorter follow-up interviews to ask additional questions and to ensure that our interpretations of the original interviews were correct. We also gave the experts an opportunity to read our drafts and to comment on our case description, which had the benefit of adding nuance to the empirical story.

As explained by Langley (1999), the challenge of theorizing from process data is to “move from a shapeless data spaghetti toward some kind of theoretical understanding that does not betray the richness, dynamism, and complexity of the data but that is understandable and potentially useful to others” (p. 694). Our research process started with a narrative strategy that involved the construction of a detailed story from raw data (Langley, 1999). This narrative was published as a separate research report for the CNES and contains an in-depth 82-page description of the uses of radiances in NWP. Our informants read this report, provided comments on the accuracy of the description, and occasionally made annotations or corrections regarding what we had misunderstood or erroneously omitted. In the second phase of the research process, we relied on a visual mapping strategy (Langley, 1999; see, for instance, Figure 2) to synthesize the data and thereby gain a better understanding of the actual transition process. This procedure enabled us to probe the tangled emergence of STT and to make sense of evolving patterns and storylines.

4. The "quiet revolution" of numerical weather prediction

The development of weather prediction is now well documented (see Nebeker, 1995; Harper, 2008). Once weather forecasting had dramatically proven its worth on D-Day, meteorology was recognized as indispensable from the military and the public, as well as, the business perspective, which led to its continuous expansion as a knowledge domain (Flemming, 1996). In light of our paper's focus, three historical occurrences are especially worth noting:

1. After World War II, weather forecasting was greatly aided by the advent of the electronic computer. John von Neumann believed that meteorology was an ideal application for computing. The Electronic Computer Project he launched at Princeton in 1946 included a Meteorological Research Project led by Junes Charney, a renowned figure in NWP. Eight years later, that project led to the first operational computer weather prediction system in Sweden in 1954, and the United States followed in 1955 (Nebeker, 1995; Fleming, 1996; Kalnay et al., 1998; Harper, 2008).
2. Under the coordination of the World Meteorological Organization (WMO), established as a UN agency in 1950, a wide-ranging and increasingly international technical system was created for meteorology. Thus, the World Weather Watch, set up in 1963, is a highly complex observation and standards-oriented network often described as an example of "infrastructural globalism" and "a vast machine" (Edwards, 1996, 2010). It collects billions of information points each day through ground stations, balloons, buoys, planes, and boats; since 1969, it has relied even more heavily on satellites, telecom systems, and data processing centers (see Figure 1). It thus constitutes a large technical system that exhibits all the characteristics of a regime in MLP terms (cf. Rip and Kemp, 1998; Geels, 2002). In particular, it combines technical

elements (measurements, instruments, computers, telecommunication systems), organizational elements (the WMO, weather services, research centers, private firms), and intangible elements (rules of the WMO, knowledge about NWP and data assimilation, etc.)[1].

3. The rise of commercial meteorology during the last few decades has coincided with increased weather-related risks in such industrial sectors as energy, transportation, agriculture, and tourism (see Randall, 2010). Today, the socioeconomic benefits of weather forecasts are estimated at more than USD 160 billion annually (World Bank, 2021). Weather satellites played a major part in this development—yet, in doing so, they triggered a "quiet revolution" (Bauer et al., 2015): a regime transition that chiefly concerned data assimilation.

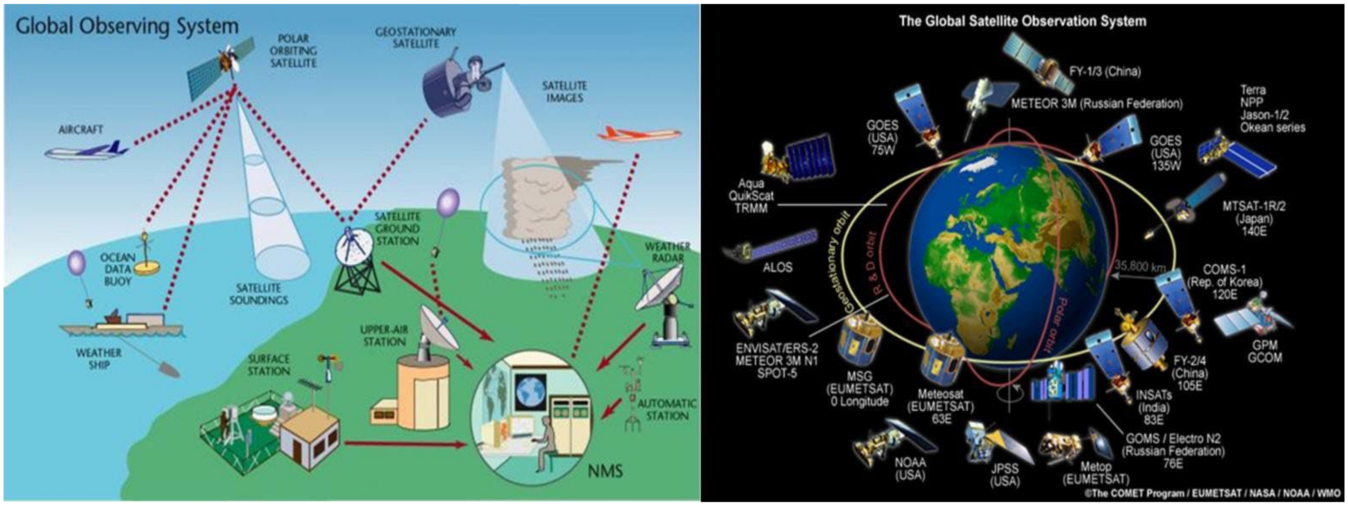

Figure 1: World Weather Watch (left) and its space components (right)

Source: World Meteorological Organization (WMO)

4.1. Emergence of a new technology: Satellite data

The idea of using satellites for meteorology is as old as satellite technology itself (RAND, 1951). This led to the launch in 1960 of the first weather satellite, TIROS-1, which provided the first global images of Earth's cloud cover—although nearly a decade elapsed before such images began to be used in daily weather forecasts (Courain, 1991). However, cloud-cover images were useless for NWP, which relied on physical parameters. Hence, in the 1960s, NASA scientists began to promote the idea of using instruments designed to explore other planets to study the Earth's atmosphere as well (Conway, 2008). These "satellite sounders" relied on complex sensing systems

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[1] The requirements of NWP account for why it is so rigorously standardized: the types of measurements, instruments, locations, measuring times, and so forth are defined by the WMO in order to guarantee, worldwide, the quality of the information on which forecasts are based.

to measure radiances and other parameters (see Menzel et al., 2018). Radiance measurements made it possible to calculate temperature, one of the most important variables in NWP models. Atmospheric temperatures had traditionally been measured with weather balloons, which provided precise temperature profiles at exact locations. The main drawback of this technique was its limited coverage, which led to the launch in 1969 of the first satellite sounder: SIRS-A. The results were promising enough to develop a series of research instruments (e.g., SIRS-B in 1970; IPTR in 1972) that finally led to an operational version, the HIRS-2, which was launched in 1978. This satellite provided data on temperature and humidity, and was the first that meteorologists considered reliable enough for its data to be integrated into their weather prediction models.

In 1979, the Global Weather Experiment conducted an integration of the satellite data as part of the Global Atmospheric Research Program. The outcome was disappointing, as results showed that weather forecasting improvements owed more to better models than to satellite data (Edwards, 2010). In fact, incorporating the new data made forecasts *less* accurate. In a famous article, Tracton et al. (1980) demonstrated the "negligible" impact of remote satellite data on NWP in the northern hemisphere—findings that triggered intense debate within the meteorological and space communities.

Perhaps the fiercest argument was between NASA, which was in charge of developing new instruments and research satellites, and NOAA, responsible for operational satellites, numerical models, and weather forecasts. After NASA sent the requirements for a next-generation sensor to NOAA/NESDIS, model developers at the NWS (National Weather Service, part of the NOAA) refused to verify them. Moreover, they adopted a position of repudiating satellite data entirely. As Conway (2008, p. 91) points out, "the satellite data did not produce better forecasts than the radiosondes carried by weather balloon, [so] the NWS only employed the satellite data from the southern hemisphere and used radiosonde data in the northern hemisphere. NASA saw little sense in continuing to spend money on a program to develop sensors whose data would not be used." As a result, NASA and NOAA agreed to end the Operational Satellite Improvement Program (OSIP) in 1982. This led to a "20 year long hiatus in new instruments for the polar orbiters," with the result that "the instrument generation of 1978, with only minor updates, continued to fly through the end of the century" (Conway, 2008, p. 92). Meteorologists had to wait until December 1998 for an improved version, HIRS-3, and until 2002 to see the launch of AIRS, a breakthrough in instruments.

4.2. First approach and tensions within the regime

The first approach that meteorologists took to the new satellite data was to make them compatible with existing operational models. This could not be stated more clearly than by the NOAA's Director of Forecasting, who said in 1969: "If you can make them look like radiosonde data, we can use them" (quoted in NRC, 2003, p. 102). Anthony Hollingsworth (1990), Head of Research at ECMWF, called this the "satellite-to-model" approach, because its goal was to force the satellite data to be compatible with existing data assimilation techniques. However, the results were underwhelming; scientific articles showed that satellite data did not improve forecast quality. Even worse, a decade after the publication of Tracton et al.'s (1980) paper, Anderson et al. (1991) demonstrated that the effects of satellite data had turned from negligible to negative. The 1980s were, in fact, a period of great disappointment for meteorology. As Philippe Courtier explained, it was "indeed terrible to know that satellites were the future of meteorology, but that we were unable to use the data efficiently at the time" (interview). Several problems contributed to these disappointing results.

One significant problem stemmed from the data themselves. Indeed, satellite sounders did not measure the temperature of the atmosphere directly; instead, they measured radiances, which are indirectly linked to temperature (and several other variables, such as humidity) through a complex physical function known as the radiative transfer equation. Even though it is easy to infer radiances from temperature and humidity, the reverse is not the case. The NOAA was therefore forced to design complex mathematical procedures (called "retrievals") that produced "pseudo-soundings" that looked like radiosonde data and were duly incorporated into NWP. Yet, these retrievals were of poor quality compared to radiosonde soundings. This was the first reason why the assimilation of poor information by complex models impaired forecast accuracy. As Woods (2006) explains in his history of the ECMWF, "from the mid-80s […] it seemed that a plateau had been reached in the Centre's forecast accuracy. […] D. Burridge [research director] had the growing feeling that in fact the Centre's Optimum Interpolation data assimilation system had been pushed to its limit. The many different kinds of data coming from the satellite instruments were just not being used optimally. Something needed to be done here, but it was not clear just what" (p. 94).

4.3. Variational assimilation: A new concept for a new regime?

The necessity to undertake retrieval procedures was not the only limitation of OI. Researchers in meteorology were also aware that OI was severely limited in terms of dealing with uncertainty. As

Olivier Talagrand, a leading scholar in data assimilation, explains: “One of the main problems in NWP is to know how the atmosphere evolves over time, but also how the associated uncertainty evolves—and OI did not handle this problem” (interview). That deficiency explains the growing gap between the initial conditions determined by OI and the model’s requirements, which resulted in a research stream dedicated to alternative methods of data assimilation. In France, Talagrand was looking for other methods (Talagrand, 1981a, 1981b). Independently, a French scholar of applied mathematics, Francois-Xavier Le Dimet, was studying the potential of “variational” methods for assimilation. The origins of this variational approach date back to the work of Yoshikazu Sasaki, a meteorologist from the University of Tokyo, who had already proposed the approach in 1955, published several papers on it in 1970 (Sasaki, 1970a, 1970b, 1970c), and later moved to the University of Oklahoma to continue his research career. Here the statistical methods of OI were replaced by the minimization of a cost function that represents the gap between the model’s initial conditions and the available information. This minimization can be done at any given time with the technique’s three-dimensional incarnation (3D-VAR); or, in a more advanced version (4D-VAR), minimization is spread over a time window in order to optimize not only the initial conditions but also the model’s trajectory.

However, at this point, the variational approach remained a largely theoretical endeavor with no real impact on practice. Yet, in 1982, Le Dimet began working with Sasaki in Oklahoma. The former’s research addressed whether the mathematical techniques of optimal control could be applied to the variational problem. Using optimal control to solve meteorological problems was highly innovative, and it led to the first draft of a paper submitted in 1982 to one of the field’s leading journals. However, the paper was rejected. Soon afterwards, a fateful encounter took place: in 1983, during a congress of the French Physics Society, Le Dimet met Talagrand. With his solid mathematical background, Talagrand was able to understand Le Dimet’s work. Le Dimet’s idea of using “adjoint” equations (see Errico, 1990) allowed scholars to minimize the variational method’s cost function for the first time. This meeting led to a pioneering paper, published in *Tellus* (Le Dimet and Talagrand, 1986), which explicated the variational method and enabled a rapid growth of research on variational assimilation at the end of the 1980s and in the early 1990s (see Courtier et al., 1993). It is worth remembering that, at this time, research on variational methods had little to do with satellite data. Le Dimet and Talagrand were far more interested in the dynamic treatment of uncertainty than in satellite data assimilation.

Immediately after their *Tellus* paper was published, Talagrand began exploring the operational potential of variational assimilation with one of his PhD students, Philippe Courtier. Courtier's own doctoral thesis (1987) and the pair's associated papers (Courtier and Talagrand, 1987; Talagrand and Courtier, 1987; Courtier and Talagrand, 1990) used several simplified models to demonstrate the potential and feasibility of variational assimilation. The assimilation problem—and, therefore, the potential of variational assimilation itself—became so great that the ECMWF and Météo-France decided to join forces to launch IFS/ARPEGE, a project with the goal of developing and implementing the variational approach. Shortly after this decision, the WMO encouraged Le Dimet and Talagrand to organize the first world conference on data assimilation. It was held in Clermont-Ferrand, France, in July 1990, and was attended by much of the data assimilation research community. Thus, regime change was gaining momentum.

4.4. Tipping to the variational regime: The IFS/ARPEGE project

The IFS/ARPEGE project was a monumental challenge, and in 1988 most experts doubted that a solution was possible. Four fundamental problems had to be solved. The first was theoretical: the methods of optimal control had never been used operationally on large-scale, nonlinear numerical models. The second and, according to our study, most pressing problem was that variational methods require a huge amount of computing power. Today, Le Dimet is crystal clear about this: "When we published the first papers this was absolutely impossible. [...] You have to put this in perspective with the development of supercomputers. Otherwise, this would have no meaning. Without it, this was a very bad idea" (interview). The problem was all the more complex because NWP models were themselves consuming more and more computing power.

The third problem concerned the immense task of integrating the new methods into operational systems. Because NWP systems rely so heavily on copious data, there are strict requirements regarding data quality, data transmission, computing speed, and so forth. A particular aspect of this problem was the need to develop an adjoint model. According to Talagrand, "This was completely new. Until then, people using adjoint methods had created the model and its adjoint simultaneously. Here, the problem was to design the adjoint of a huge model that already existed. Obviously, nobody had ever done that" (interview). The fourth and final problem was the question of radiances. Although proper assimilation of satellite radiances was hardly the project's *raison d'être*, the question soon became central. Indeed, the coverage provided by satellites remained a breakthrough innovation for meteorologists. All four of these problems were critical, and required computing power that was unthinkable at the time. As Le Dimet explains: “Had I known [in 1982] what it cost [in computing power], I would have given up immediately [laughs]. We didn’t expect the many difficulties [in operational implementation]” (interview).

According to Andersson and Thépaut, who were key figures in the project, IFS/ARPEGE was “one of ECMWF’s biggest-ever projects” (Andersson and Thépaut, 2008). The project mobilized about 30 individuals over a 10-year period, and most of the authors’ PhD students worked on the project. As Thépaut states, “This was a gigantic endeavor: we had to develop everything from the adjoint models to the handling of satellite data” (interview). Furthermore, it was a risky decision: “You had to be a visionary, because when Talagrand and Courtier published their 1990 paper, the computing power was not available” (interview). Philippe Courtier was widely recognized as the driving force needed to assume the project’s leadership. As a pioneer of variational methods, he played a major role in the project at the ECMWF (during 1986–1988 and 1992–1996) and at Météo-France (1989–1991). In particular, Courtier brought together three crucial areas of expertise: data assimilation for NWP, the mathematics of optimal control, and computing.

The IFS/ARPEGE project began in the summer of 1987 (see Table 2). The first phase consisted of completely recoding the prediction model, which was incompatible with variational methods. That task required two years of intense work—partly because the team took this opportunity to change the code’s architecture, making it modular and more flexible, for the sake of future development. After this phase, the team returned to the design and implementation of variational data assimilation. They soon realized that the amount of work needed to complete the task had been seriously underestimated. So, in 1991, the completion date was postponed from 1993 to 1996.

Table 2: Key events and dates in the IFS/ARPEGE project

Time	Event	Comment
1987, July	Initiation of the development of IFS/ARPEGE.	This was a critical step for making the key players agree on the overall action plan required to overcome the problem of the reverse salient.
1988, October	Official launch of the IFS/ARPEGE project. The timeline for the project that was presented at initiation indicated completion of the project in 1993 for 4D-VAR.	This exerted the time pressure needed for the action plan to gain momentum.
1991	New completion date adopted. Project somewhat delayed but progress had been made. Revised completion expected in 1996 because of the extraordinary demand for computing power and the need for advances in algorithms and software development.	At this stage, the key players were becoming increasingly aware of how much the project's success depended on computing power.
1994, March 2	Introduction of the IFS model on the Cray C90 computer (Cy11r7).	This step was necessary to ensure sufficient computing power.
1996, January 30	3D-VAR becomes operational (Cy14r3). Decision made not to migrate OI to the new Fujitsu VPP 700.	This marked an irreversible commitment to the variational approach.
1996, September 19	3D-VAR is migrated from Cray (shared memory) to the Fujitsu VPP 700, which relied on distributed memory technology (Cy15r5).	This change in the project's technology strategy opened up new avenues for solving the underlying problem.
1997	3D-VAR becomes operational at Météo-France.	This stage was critical for experimenting and trying out the new solution.
1997, November 25	4D-VAR becomes operational at ECMWF (Cy18r1).	This date saw the first operational use of 4D-VAR.
1999, June 20	4D-VAR becomes operational at Météo-France.	This date marked the start of the operational diffusion of the 4D-VAR approach.

Source: Based on Andersson and Thépaut (2008) and interview data.

The root of the problem was the computing power needed for variational assimilation. Given the strict requirements of operational weather prediction and the forecast cycle's extremely short time window (2–3 hours), variational assimilation increased the computing cost by a factor of 100—a matter of fierce debate between supporters and opponents of the variational approach. The breakthrough came in 1992 during a conversation among Courtier, Thépaut, and John Derber[2] of the NOAA, who was then working at the ECMWF. This conversation led to the development of a cost-saving method: the incremental approach (Courtier et al., 1994). That method allowed for a

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[2] J. Derber was the leader of the team working on variational data assimilation at NOAA/NWS, following in the footsteps of Le Dimet, Talagrand, and Courtier (see Lewis and Derber, 1985; Derber and Wu, 1998; Derber, 2011).

tenfold reduction in computing costs, which “de facto rendered the 4D-VAR feasible on the ECMWF supercomputer” (Thépaut, interview).

The assimilation of radiances became a core question one year after the launch of IFS/ARPEGE, when “it was recognised that variational methods would provide a solid foundation for the assimilation of satellite data” (Pailleux et al., 2015, p. 25). The growing importance of this question is evident in the proceedings of the WMO Clermont-Ferrand symposium. In his opening address, Hollingsworth (1990), Head of Research at ECMWF, compared two approaches to handling these data: the satellite-to-model method (see above) and the new, variational, model-to-satellite method, which he said “has still to be tested in real size problems.” He underscored the complete reversal that occurred during the transition from OI to 3D/4D-VAR. Indeed, in the variational approach, the process begins by calculating radiances from the forecast model. The variational algorithm then modifies “model radiances” to make them as close as possible to the satellite-measured radiances. One advantage of this procedure was that it eliminated any need for the complex retrieval process and all its approximations. However, in 1990, this method amounted to little more than theoretical assumptions and abstract ideas.

The work on radiances was led by John R. Eyre (Eyre et al., 1993; Eyre, 2007) and J.N. Thépaut (Thepaut and Moll, 1990)[3]. It proved to be prohibitively difficult, given the complexity of the algorithms and of the physical processes involved. An illustrative episode occurred in 1993. By this time, most of the work had been done: thanks to the incremental approach, the variational process worked, and was tested extensively before moving to the operational phase. However, results from the assimilation of radiances remained disappointing, and had no significant effect on forecast accuracy. During a brainstorming session, Courtier channeled his vast knowledge of weather prediction to realize that the problem could be traced to fine-tuning of the “background error covariance matrix,” which was exceedingly complex yet played a vital role in the accuracy of forecasts. The variational approach was finally on its way to success.

4.5. Regime change: Diffusion of the variational approach

All this work eventually led to the implementation of the variational approach for 3D-VAR at the ECMWF in January 1996, just one month after its launch by a NOAA team led by J. Derber. This

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[3] Thépaut, who began his PhD in 1988 under the supervision of Talagrand and Courtier, was instrumental to implementing 4D-VAR at the ECMWF and Météo-France. At the time of our data collection, he headed the ECMWF’s Data Division. He is now Head of Copernicus Climate Change Services (C3S) at ECMWF.

was something of a trial run, since only one year later, in 1997, the ECMWF moved to 4D-VAR—the ultimate goal of the project. Météo-France followed with 3D-VAR in 1997 and 4D-VAR in 1999 (Figure 2 provides an overview of the transition). The results were so spectacular that they triggered a worldwide diffusion of variational assimilation. For instance, the UK Met Office followed in 2004, the Japan Meteorological Agency and Environment Canada in 2005, and the U.S. Naval Research Laboratory in 2009 (Bauer et al., 2015). Within a relatively short period, all the world's leading weather forecasting centers had adopted variational assimilation. Undeniably, the new approach proved to be "a systematic method to introduce any kind of data in the assimilation process" (Talagrand, interview). For example, GPS Radio Occultation data were assimilated into NWP at the ECMWF in 2006—a very short timeframe for a new type of data[4] (Kuo et al., 2001; Eyre, 2008). The IFS/ARPEGE code and variational scheme are still in use at ECMWF and Météo-France today, 20 years after their first implementation, which offers impressive proof of their power and resilience (Pailleux et al., 2015).

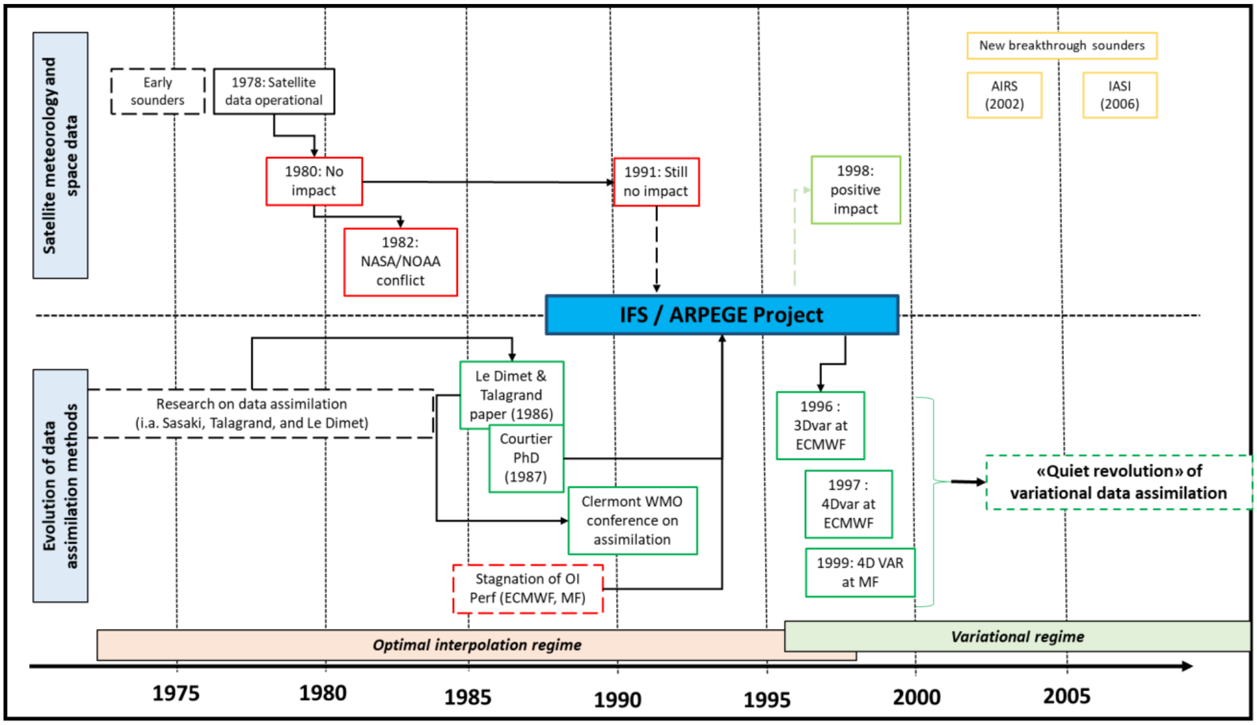

Figure 2: Overview of the transition process

(Solid line indicates direct relationship, dotted line indicates indirect relationship)

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[4] Indeed, GPS-RO data were assimilated as soon as they became available in real time (see Eyre, 2008), whereas it took 20 years for radiances.

5. Discussion

What we observe in the meteorology case is a STT that was triggered by tensions over the modeling of uncertainty and by the arrival of entirely new measurement instruments: satellite sounders. As we have shown, the reverse salient of data assimilation played an important role in holding back system-wide advancements at first. However, it later became pivotal in creating a common focus and an impetus among the actors involved. Nevertheless, it took almost 20 years to overcome the system's reverse salient, which called for the development of knowledge and the mobilization of resources, as well as the establishment of a common arena where the main stakeholders could interact.

Indeed, data assimilation was a persistent obstacle to advancing the entire weather prediction system, because it hindered a shift from the old OI regime to the new variational regime. The transition was more than merely technological. It also concerned the regime's intangible and institutional elements (Geels, 2002; Dougherty, 2016) – here, the conceptual breakthrough of using the mathematics of optimal control to overcome the limitations of OI. So, what does this case tell us about the unfolding of STT, and about the emergence and the nature of agency in enabling this particular type of transition?

To pave the way for an in-depth analysis, we argue that this is not an instance of one of the traditional pathways identified in earlier MLP research. Instead, this case may represent an example of a particular kind of transition pathway: *regeneration*. This pathway, we believe, complements and adds granularity to the well-known typology introduced in Geels and Schot (2007), by highlighting STT initiated by actors *within* the regime *without* significant changes to landscape pressure. In the following, we will address the characteristics of regeneration, and, in that context, discuss the role that the reverse salient plays in hindering and/or advancing regeneration. Following that, we will elaborate on the role of project-oriented agency in enabling regeneration and, in the final section, propose a process model of project-oriented agency in such transition pathways.

5.1. Regeneration and reverse salients

As explained in the theory section, MLP research started with a strong bottom-up orientation: radical innovations are developed in niches before modifying the regime when landscape pressure becomes strong enough. The paper by Geels and Schot (2007) introducing the four pathways influenced the direction of this research. Their foundational idea was that transitions depend on the interaction between landscape pressure and the readiness of niches. More precisely, their characterization discerns three important aspects.

First, Geels and Schot's analysis highlights that transitions vary depending on the speed of change. Second, they suggest that relations among the framework's various levels are inherently complex, and that niches are not necessarily the chief drivers of STT. Third, they emphasize the "symbiotic" versus the "competitive" relationship between the niche and the regime—i.e., the extent to which they are competence-enhancing, or trigger regime change (2007, p. 406). These ideas are developed further by Geels et al. (2016), who demonstrate that the enactment of the different pathways takes more complex forms than had been suggested in the original typology; for instance, there are different kinds of new entrants and, in addition, incumbents may also reorient toward radical innovations. However, all four pathways have one feature in common: the existence of strong landscape pressures serving as triggers for STT.

Regeneration differs from the other pathways in three important respects: (i) the limited role of landscape pressure; (ii) tensions arising from within the regime that crystallize around a specific reverse salient; and (iii) the creative accumulation of new competencies that leads to the implementation of a non-symbiotic solution to overcome the reverse salient.

First, from our findings, one cannot reasonably argue that landscape pressure played a major role in this case. As seen in the case description, there was no significant change in landscape pressure, no "disruptive shock" or "avalanche change" that played a vital role in driving the transition. Instead, we observe a sustaining pathway similar to the "reproduction regime" (Geels and Schot, 2007)—i.e., a continuous demand, by the same users (both civilian and military) for more accurate forecasts and an extension of the uses of meteorology (Edwards, 2010; Randall, 2010; Kull et al., 2021). This differs from the Geels and Schot typology, which, on the contrary, presupposes that significant changes in landscape pressure prompt the transition (e.g., the pressure from hygienists and doctors in the switch from cesspools to sewer systems). Neither our interviews nor the detailed accounts of the histories of meteorology indicate any major change of landscape pressure during the time period covered by our study.

Second, our findings demonstrate that tensions and misalignments within the current regime (Geels, 2004) may in fact play a much more critical role in triggering the actual transition. Our case study reveals four such tensions that, in combination, spurred the transition:

a) a scientific dissatisfaction with current data assimilation methods, especially concerning the handling of uncertainty;
b) a growing gap between the needs of the models and the performance of OI with respect to determining a forecast's initial conditions;
c) a stagnation in the performance of NWP at the ECMWF (and also at other weather services); and
d) the inability to use satellite data efficiently—a tension that intensified in the late 1980s and the early 1990s, when the number of satellites was increasing.

This last tension was partly "external" in the sense that the first satellite was launched by NASA to experiment with space sounders on the earth's atmosphere. However, this quickly became an internal problem, because instruments were subsequently launched on NOAA satellites to improve operational forecasts. This sudden entry of a new type of instrument had a definite impact on the STT in meteorology. The other three tensions were not external; in fact, they emerged from within the regime and were driven either by researchers and experts with deep knowledge of operational weather forecasting or by weather forecasters with a research background who were in charge of operations. For instance, when Philippe Courtier was writing his PhD on variational methods, he also had operational responsibilities for optimizing the OI algorithm. The external influence in our case study was due to Le Dimet, who had not worked in a meteorological lab but had a background in applied mathematics and did his PhD in meteorology, and it was from this input that the conceptual breakthrough came. What is interesting is that these tensions crystallized around the reverse salient of data assimilation, which appears to be the chief problem that hindered the progress of the entire system.

Third, we observe the creative accumulation of new variational competencies in different research centers, such as the University of Oklahoma, the Laboratoire de Météorologie Dynamique in Paris, NOAA-National Weather Service, and the research departments of operational centers such as Météo-France or ECMWF. All these teams worked on simplified models meant to demonstrate the variational scheme's potential. They represent the niches in our case, which constituted the "protected spaces" that shielded, nurtured, and progressively empowered the new approach (Smith and Raven, 2012), where researchers could experiment with new methods without disrupting operational forecasts. It is important to note that key researchers moved back and forth between the various niches and the regime (most notably Phillippe Courtier, who pioneered the research and then led IFS/ARPEGE alternately at ECMWF and Météo-France, and Olivier Talagrand[5]).

However, what is interesting for the account of the regeneration pathway is that variational data assimilation was far from symbiotic. As was apparent in the empirical study, there was a huge gap between experiments and the operational system. Implementing 3D/4D-VAR implied, for instance, the recoding of the entire prediction models and the design of new algorithms to reduce the computing costs, as well as the fine-tuning of the B matrix. The supercomputers, in particular, were a bottleneck[6]; an innovation in NWP could only be implemented if there was proof that it was better, in real settings, than the existing regime. Yet, the true operational conditions were only available in those relatively few weather centers with sufficient computing power, so research and operations had to be closely connected in order to enable system-wide change. Thus, in the regeneration pathway, the regime transforms itself from within in response to internal and idiosyncratic tensions, leading to a reverse salient. Yet, unlike the case of the other transition types in the typology of Geels and Schot (2007), this transformation occurs (a) without significant landscape pressure and (b) with a combination of continuity and change that encompasses extant systems, methods, and knowledge from the past paired with their brand-new and far from symbiotic elements.

Thus, the regeneration pathway highlights the regime's ability to renew itself through the creative accumulation of competencies (Bergek et al., 2013). The accumulation of competencies, in turn, enables the reverse salient to be identified and overcome in the absence of new external pressure, even if that ability presupposes the design of "non-symbiotic" innovations. In this respect, regeneration represents a potential third pathway that is distinct from both transformation and reconfiguration, in which the regime evolves to accommodate novelty; whereas in substitution and de-alignment/realignment the existing regime is *replaced* by a new one (see Table 3 for a comparison of the three pathways). It also demonstrates, in accordance with the MLP structuration interpretation, that the structures of the new regime can evolve from within the old regime.

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[5] Olivier Talagrand—a prominent member of the LMD and a central figure in our story—worked at the Laboratoire de Météorologie Dynamique, but also with Météo-France and at the ECMWF, where he headed the scientific committee. He was awarded the silver medal of the French CNRS in 2004 for his pioneering work on variational data assimilation.

[6] Actually, there were seven successive generations of supercomputers at ECMWF from 1977 to 1997, including four during IFS/ARPEGE. One of the project's major decisions was *not* to migrate OI to the last generation of supercomputer, making the transition inevitable.

Table 3: Regeneration vs. transformation and reconfiguration

	Transformation	**Reconfiguration**	**Regeneration**
Definition	This pathway is led by landscape pressures that stimulate incumbent actors to gradually adjust the regime, when niche innovations are not sufficiently developed.	This pathway is based on symbiotic niche innovations that are incorporated into the regime to solve local problems and trigger further (architectural) adjustments under landscape pressure.	This pathway is based on non-symbiotic niche innovation introduced to solve a reverse salient without significant changes in landscape pressure.
Type of landscape pressure	Moderate/"Disruptive" (Geels and Schot, 2007)	Moderate/"Disruptive" (Geels and Schot, 2007)	Similar to reproduction: no significant changes (more of the same uses and users).
Nature of the relation between niche and regime	- Not yet sufficiently developed - Symbiotic	- Radical innovation - Symbiotic - Initially aimed at solving local problems, but may trigger architectural changes	- Radical innovation - Non-symbiotic innovation to overcome the reverse salient
Main driver	Landscape pressure on incumbents	Landscape pressure on incumbents confronted with "local problems"	Project-oriented agency established by incumbents
Emblematic case	Mid-19th century transition from cesspools to sewer system in in the Netherlands	Emergence of mass production in the U.S. (e.g. the Ford Model T)	Transition of NWP from OI to 3D/4D-VAR

It is therefore logical that several features of the old regime remain in place while others undergo substantial change (see Table 4). In our case, regime actors survived even though 4D-VAR's implementation was far from symbiotic; it amounted to a clear conceptual break from the preceding regime. This interpretation is supported by our interviews with Courtier and Talagrand, who underline that proponents of OI failed to understand the variational scheme because of their limited mathematical background. This fact may also explain why it took so long to implement the approach at operational centers around the world. For sure, regeneration may imply radical changes to the regime—both conceptually and technically. It required a complete redesign of the forecasting system. However, regeneration probably cannot occur unless the most significant regime actors mobilize and establish a sense of direction for their joint action[7]. This is where project-oriented agency enters the scene.

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[7] Another example of this type of transition is studied by Le Masson et al. (2012) in the case of semiconductors. These authors report that the International Technology Roadmap for Semiconductors (ITRS) played a critical role in the industry's continuous transformation—to the extent of altering the dominant design.

Table 4: Continuity and change in the NWP case

Continuity: **Reuse of existing systems, methods, and knowledge**	***Change:*** **Implementation of radically new systems, methods, and knowledge**
WMO	Satellite data
Weather centers (ECMWF, Météo-France)	New data centers and new organizations to handle the data (NOAA NESDIS, EUMETSAT)
In situ measurement systems	Coding/architecture of the model
Prediction models/atmospheric physics	3D/4D—Variational data assimilation
Supercomputers	Conceptual foundation: mathematics of optimal control

5.2. Project-oriented agency and STT

As we saw in the literature review, the role of projects is now firmly established in MLP research. For instance, sequences of projects played a central role in the Strategic Niche Management approach as a way to implement transition (Raven and Geels, 2010). More recently, Turnheim and Geels (2019) studied the impact of landmark projects in infra-system transitions, and argued that more attention needs to be directed towards the process that takes place within actual projects to enable STT. However, earlier literature that focused on the meso level tended to neglect how transition depends on events that transpire at the micro level (Geels et al., 2016, p. 898). This limits our understanding not only of collective action, but also of the establishment of agency in complex innovation settings.

In contrast to earlier research, our study underlines the importance of analyzing action and events at the project level to understand how joint problem-solving evolves, and thereby how project-oriented agency enables STT. As our empirical study shows, the IFS/ARPEGE project played a prominent role in overcoming the reverse salient of data assimilation. Thus, it seems especially important to study how actors work on the reverse salient to capture the micro-level dynamics of STT. In particular, this would pave the way for a better understanding of the nature of regeneration—and how it merges continuity and (sometimes radical) change—when examining actors and their design choices (Hargadon and Douglas, 2001). In the case of the quiet revolution of NWP, we observed that the interplay between continuity and change was vital during all stages of the transition process, namely:

1. in the conceptual breakthroughs by Le Dimet and Talagrand;
2. in the first demonstration of the method's feasibility by Talagrand and Courtier;

3. for Le Dimet and Talagrand's lobbying to bring the WMO on board via the Clermont-Ferrand International Symposium on data assimilation;
4. in the implementation work, led by Courtier, that brought together the required knowledge and competences: NWP, computing, and the mathematics of optimal control.

As demonstrated in earlier research on innovation, creating an impetus (Burgelman, 1983) and coordinating various—and sometimes previously disconnected—areas of expertise (Van de Ven, 1986; Dougherty, 2016) are major challenges to the management of innovation. Setting up a project is one means of surmounting these difficulties, as witnessed by the history of technology and innovation (e.g., the Manhattan, SAGE, and ARPANET projects; see Hughes, 1998; Lenfle and Loch, 2010; Davies, 2017). These considerations may explain why organizations so frequently rely on projects to manage the innovation process (Davies et al., 2018). For instance, Lenfle and Söderlund (2019) examine the WWII radar project, and show how large-scale innovative projects enable new connections across diverse disciplines that are needed for the innovation to succeed. Referring to Galison's (1997) work on interdisciplinary coordination, the authors describe the arena for these connections as a *temporary trading zone*. Furthermore, studies have established that managing exploratory projects often requires a particular set of managerial approaches and mechanisms (Loch et al., 2006; Shenhar and Dvir, 2007; Lenfle, 2008; Brady and Nightingale, 2011; Sommer et al., 2009; Lenfle and Loch, 2010 : Lenfle et al., 2019) that differ markedly from the conventional project management arsenal (cf. Nightingale and Brady, 2011; Davies et al., 2018). These findings echo evidence from empirical studies of STT. For example, Raven's (2005) study of biogas development in the Netherlands and Denmark stresses the power of "parallel development patterns" in which different solutions are explored simultaneously—a well-known approach to managing high-uncertainty innovative projects (see e.g. Klein and Meckling, 1958; Nelson, 1961; Loch et al., 2006; Lenfle, 2011; Loch and Sommer, 2019). This approach broadened the product's market, accelerated learning, and reduced the likelihood of actors getting stuck on one particular technological path.

Indeed, our case confirms that a project can play a pivotal role in the transition process (cf. Hughes, 1998). In fact, the IFS/ARPEGE project served as a catalyst that enabled the tipping from one regime to another. Following Emirbayer and Mische's (1997) suggestion, we note that project-oriented agency is rooted not only in the past (as it embodies a thorough understanding of the nature of the complex innovation system), but also in a vision of the future. But what explains the "tipping effect" that projects have on STT? Our research delineates several components of a theoretical account for project-oriented agency in STT through regeneration. From our analysis, and from the preceding literature on the management of innovative projects, we discern four key elements that constitute the foundation of project-oriented agency in the regeneration pathway. Below, we will analyze how these four elements developed over time in the transition from regime destabilization to global diffusion (Table 5).

Table 5: Four elements of project-oriented agency in regeneration

Element	**Description**
Goal agreement. Common understanding of the problem(s).	A shared understanding of the nature of the problem(s). This understanding encourages key actors to mobilize resources and develop new knowledge.
Resource and knowledge mobilization. Critical mass of resources and knowledge.	A critical mass of key actors brought together with sufficient resources in terms of funding, instruments, equipment, and knowledge. These circumstances create the variety needed to solve the problem that has been identified (Van de Ven, 1986).
Temporary trading zone where main actors can interact and establish collaboration.	A project that operates as a trading zone (Galison, 1997) provides a collaborative arena that facilitates the integration of diverse expertise and knowledge among a wide variety of actors (Lenfle and Söderlund, 2019). Such a trading zone allows sufficient contact and integration among the actors involved, and provides a forum to agree on how to act on the reverse salient.
Temporal framework that defines the impetus to enable action.	Actors agree on the temporal framework that induces a tipping of the regime and thus facilitates the impetus to the transition (Gersick, 1988; Brown and Eisenhardt, 1997; Hughes, 1998; Dougherty, 2016).

First, the creation of a project means that agreement has been reached about the nature of the problem at hand—although the problem still might not be well defined, strictly speaking. Indeed, the logic of these projects remains abductive in nature (Dougherty, 2016). However, formulating a project requires agreement on the delineation of the problem and a common understanding of the reverse salient: what it is and how it might be counteracted. For NWP, this issue concerned the limitations of current assimilation methods and of the variational approach as a solution.

Second, creating a project leads to mobilizing resources and combining the expertise of the actors involved. These resources can be diverse and include (*inter alia*) staff, funding, knowledge, instruments, and institutional networking. Thus, it is essential to accumulate a critical mass of resources for attacking the reverse salient.

Third, the project establishes a powerful coordination mechanism to ensure collaboration among human resources and expertise. It provides a collaborative arena that facilitates the integration of diverse expertise and knowledge, which might otherwise have remained dispersed and thus incapable of generating the agency needed for a successful transition. Setting up such a trading zone is fundamental for innovation and for organizing creative confrontations among those with differing expertise (Lenfle and Söderlund, 2019).

Fourth, launching a project changes the temporal framework of the entire process (although this factor seems understated in the literature). Certainly, projects involve deadlines and milestones that impart pace to what might previously have been a "fuzzy" transition process. The resulting change in pace allows actors to manage that process by regularly discussing the project's evolution and adapting their actions accordingly. This approach creates the sense of order and urgency necessary for innovation and also gives actors a sense of control (Gersick, 1988; Brown and Eisenhardt, 1997), or what Dougherty (2016) refers to as "event-time pacing" in complex innovation projects.

5.3. Toward a process model of project-oriented agency

Paraphrasing Van de Ven (1986), innovation management is fundamentally a "process problem" in which "innovative ideas are implemented and institutionalized" (p. 591). This is especially true of STT, which implies a shift from one regime to another. By relying on the concept of project-oriented agency, how can we make sense of the "quiet revolution" of NWP, and of its process dynamic?

Our study discerns five essential phases in the regeneration transition pathway that shed light on the formation of project-oriented agency enabling the actual transition. Our findings indicate that the establishment of project-oriented agency plays a central role in all five phases; in the initial phases it is more oriented towards identifying problems and directing collective action, while in later stages it is targeted toward implementation and diffusion-oriented activities concerning the concrete results and solutions developed in the project. Below, we detail the five phases of the process model through our case-study findings. To simplify the model, we present the phases in a linear fashion; however, based on our findings, we underscore that they can overlap significantly, and individual phases may well involve their own iterations.

Phase 1: Regime destabilization and creative accumulation. The process begins with the destabilization of the existing regime, for both inner reasons (in our case, handling of uncertainty) and outer reasons (the emergence of satellites as new measurement systems). This leads different actors to explore various alternatives to solve the underlying problems associated with the destabilization. Two parallel developments occur during this phase: one centers on the actual destabilization of the regime and, simultaneously, the creative accumulation of competence makes actors increasingly aware of both potential problems and challenges with the current regime—and, also, that there might be other solutions available that need to be explored. In the NWP case, the process began with the launch of SIRS-A, which triggered the exploration process in which different types of instruments were launched and scientists began exploring and experimenting with the new data. This phase ended with the launch of HIRS-2 in 1978, when meteorologists considered the data to be ready for operational use. Simultaneous but independent work by Sasaki triggered new research on variational data assimilation.

Phase 2: Reverse salient identification. In the second phase, the exploration process allows for the identification of one or more reverse salients. In our case, these were the limitations of existing data assimilation technologies, and of the possible alternative solutions (here, the variational approach). In this regard, our evidence clearly resonates with Hughes' classic studies of the role of reverse salients in driving technology development in LTS. Our case highlights the centrality of understanding, detecting, and acting on the reverse salient to make regeneration possible. However, our evidence indicates that the reverse salient is also central to the establishment of project-oriented agency, as it sets the common focus among actors and creates a foundation for collective action in subsequent phases. In our case, this phase began after evidence was presented that satellite data had a negligible effect on forecast accuracy. That evidence led to a long-lasting conflict between NASA and NOAA, which stalled the development of instruments. Meanwhile, researchers in meteorology sought alternative data assimilation methods—although without a clear connection to the satellite issues. This phase ended in 1986 with the publication of the first paper by Le Dimet and Talagrand, which demonstrated the potential and feasibility of variational data assimilation. It became increasingly evident that data assimilation was the reverse salient delaying a better handling of uncertainty and the integration of satellite data, and that variational approaches were a viable solution.

Phase 3: Project formation. On this basis, in the third phase, a project can be established that focuses on the design of a solution to counteract the reverse salient. At this stage, the four elements of project-oriented agency described in Table 4 are in place; the primary focus is on solving the challenges associated with the reverse salient. In that respect, there is clearly a basis for generating the project-oriented agency and impetus that seem critical to project success. This agreement leads to the establishment of a "temporary trading zone" in which collaboration between actors with diverse expertise can unfold. This signifies the start of collective action to focus on a specific target.

The 1986 paper unlocked research on this question, and the next two years set the stage for the IFS/ARPEGE project. In 1990, the Clermont-Ferrand International Symposium on data assimilation, under the WMO's aegis, was a milestone that marked the convergence between research in data assimilation and satellite data problems. It also signified acknowledgement by the entire community and a shift, at the institutional level, toward the variational scheme.

Phase 4: Project integration. This phase focuses on the integration of dispersed knowledge and competences. The actors focus on the implementation of the solution, which may be a long and costly process of continuous innovation—as it was in our case. The IFS/ARPEGE project functioned as a catalyst for "tipping" from the old regime to the new one; it provided impetus and resources, and elicited commitment while ensuring that actors were aligned with the initial agreement on solving problems resulting from the reverse salient. The integration phase began with the implementation of IFS/ARPEGE, which was formally launched in 1988. It included the change of ECMWF, NOAA/NCEP, and (shortly afterwards) Météo-France to the new variational regime—a change in orientation that spilled into the next decade.

Phase 5: Global diffusion. In the fifth phase, we observe a wider diffusion of the new technology, thanks to the success of the first set of installations. The new technology has demonstrated its power to overcome the reverse salient and has led to other projects. It is "systematically replicated," as argued by Turnheim and Geels (2019). This confirms the success of the entire regeneration process and indicates that a regime shift has taken place. This corresponds to the "quiet revolution" described by Bauer et al. (2015)—i.e., the spread of the new variational approach to other major meteorology centers around the world. Today it has replaced OI and is the dominant approach in meteorology. Moreover, it allows the operational use of a wide variety of new data, such as GPS-RO (Kuo et al., 2001 ; Eyre, 2008).

Combining the elements that capture the nature of project-oriented agency with the five phases identified in our case study gives us a more coherent and complete view of the establishment and evolution of project-oriented agency in regeneration. Table 6 presents an overview of the five phases and how the four elements of project-oriented agency develop over time. As mentioned before, this model is strongly linear, and offers an ex-post simplification of a successful case. However, we know from earlier research on innovation processes that phases are oftentimes overlapping and even chaotic (Van de Ven et al., 1999), and this holds for project-oriented agency as well. Thus, the model should be viewed as an archetype that helps us identify conditions of project-oriented agency in the regeneration pathway, not as a prescriptive model.

Table 6: A process model of project-oriented agency in regeneration

	Phase 1: **Regime destabilization**	***Phase 2:*** **Reverse salient identification**	***Phase 3:*** **Project formation**	***Phase 4:*** **Project integration**	***Phase 5:*** **Global diffusion**
I. Goal agreement. Common understanding of the problem.	Growing awareness that there are potential problems that need to be resolved, and that hinder system-wide advances. Actors within the field are exploring these problems, and beginning to actively search for alternatives.	A more precise understanding of what the reverse salient actually is, and some kind of agreement on which part of the system is holding back system-wide advances. The focus shifts towards narrowing the set of choices and problems.	Explicit agreement about the nature and existence of the reverse salient and how it could be overcome. Major stakeholders hold a shared view of what is holding back system-wide advances, and agree on the need for collective action to solve the problem.	Implementing the new solution. Project setup, including articulation of the project mission. Innovation in specific dimensions may continue.	Solution to the reverse salient is now operationally demonstrated. Solution to reverse the salient problem implemented on a wider scale.
II. Mobilizing resources and knowledge. Critical mass of resources and knowledge.	Creative accumulation of knowledge, building a better understanding of the problems with the current system, and also a growing understanding of the alternatives. Limited commitment; mostly small-scale experiments in research labs.	Knowledge developed about the nature, technologies, and implementation problems of the reverse salient. Key actors establish a coherent understanding.	Networking to set up a project and involve the community. Identification of project mission and key players. Evaluation of the risks and opportunities of the potential project.	Project as catalyst. Identification of key players who will fill critical roles in the project.	Replication of the solution (Turnheim and Geels, 2019). Improved understanding of implementation problems and linkages between solution and operations.
III. Establishing a temporary trading zone: an arena where the main actors can interact and establish collaboration.	Trading zone not yet established. Interaction occurs in various other settings, such as conferences. As yet, there is no focused and formalized forum where people can meet to share experience and build knowledge around the limitations of the current system.	The arena is gradually developed. For now, several research centers/ departments are working on the problem, although not in a coordinated manner.	Emergence of common project to enable transition. Creation of a project in which collaboration can unfold. Temporary trading zone is developed to enhance collaboration.	Explicitly defined project organization with clear management and leadership roles. Alignment of the different actors. Integration of diverse knowledge toward the implementation of the solution.	Collaboration arena between project phase and operations implemented, allowing experience to be shared on a global scale. Other projects are launched.
IV. Temporal framework, impetus, and direction.	Awareness of the limitations of current approaches, and that something needs to be done. Focus is on the nature of the problem.	Identification and specification of the problem. As yet, any solution is identified mainly at an abstract theoretical level. This triggers an awareness that the reverse salient could be overcome.	Awareness spreads within the community. Collective action to focus on a specific solution. A stronger focus on how to solve the problem.	Implementation of the solution. Project provides the impetus for tipping from the old regime to the new one.	First implementation as exemplary case. Wide dissemination of the new method and global recognition of its merits.

6. Conclusions and implications

Focusing on the issue of agency in STT pathways, this research confronted the Geels and Schot (2007) classic typology of transition pathways with the case of the "quiet revolution" that radically transformed numerical weather prediction. This paper adds substance and nuance to the "agency turn" in MLP research—i.e., the move away from macro-historical case studies to a stronger focus on meso- and microfoundations—by suggesting an analysis centered on the micro level of STT, in line with the suggestions of Turnheim and Geels (2019) and Kohler et al. (2019). On that note, this paper makes three main contributions.

First, we empirically explore the quiet revolution in meteorology as a revelatory case of *regeneration*. We argue that this case represents a tentative fifth distinct type of STT pathway in which the regime transforms itself without significant changes in landscape pressure, by implementing non-symbiotic innovation to overcome the reverse salient. This leads to the combination of existing elements with radically new ones. One main enabler of this revolution was the introduction of weather satellites, although it was more proximally driven by the launch of a large-scale project that developed and implemented a new approach to data assimilation. As our study demonstrates, this new approach counteracted the reverse salient associated with data assimilation. Of course, the regeneration pathway is tentative and, so far, only based on a single case study; further research is needed to address additional cases, and to explore the pathway's relevance in other STT contexts.

Second, our paper introduces a particular type of agency: *project-oriented agency*. We demonstrate that project-oriented agency was the single most important enabler of the transition we study. We identify four elements of project-oriented agency: agreement on goals, resources and knowledge, a trading zone for cooperation, and impetus. Our study indicates that the IFS/ARPEGE project was instrumental in the tipping of the new regime by demonstrating the power of 4D-VAR data assimilation, and by serving as a reference for future projects. The paper also demonstrates that focusing on the micro level, including the actions taken by key experts within the project, sheds new light on MLP concepts such as "local problems," which may actually lead to radical changes.

Third, the paper suggests a process dynamic that is crucial in establishing project-oriented agency, enabling regeneration, and, thus, initiating the tipping from one regime to another. We identify five primary phases that seem critical for regeneration and for actors to overcome challenges associated with the reverse salient. Additionally, we show how the four elements of project-oriented agency emerge progressively to enable the transition; they add a catalytic effect and impetus that, in our case, led from OI and 4D-VAR to the STT and the ensuing expansion of the use of data satellites in NWP. Here again further research is needed to confirm this process.

This study bears several implications. The theoretical implications relate to studying regeneration as a distinct pathway in which transition emerges from within through tensions in the existing regime and the gradual awareness of problems caused by a reverse salient. Thus, our theoretical implications suggest that research should pay more attention to the role played by reverse salients in regeneration, and in the consequential need for focused collective action—that is, for project-oriented agency.

Finally, as called for by Geels (2011), we highlight the potential cross-fertilization between the fields of transition research and innovative project-based organizing. There is no doubt that a dialogue between the two fields may be fruitful for both camps (Davies et al., 2018 : Midler et al., 2019). The practical and policy implications of our research are associated with regeneration, reverse salients, and project-oriented agency. We highlight the necessity of appreciating regeneration as an STT pathway that differs from the other transition pathways. In regeneration, the establishment of project-oriented agency may be pivotal, yet also hardest to bring about, given historical lock-ins and the possibility of disagreements among the many players involved. In sum, identifying the reverse salient and establishing project-oriented agency are indispensable activities for the success of a transition through regeneration.

The case exemplifies a problem that is growing in interest and relevance for a number of other innovation settings—most notably, the assimilation of big data and the design of breakthrough algorithms, as in artificial intelligence. This is increasingly relevant in a range of industries where the main challenge is how to assimilate, process, and exploit massive amounts of information. More research is needed to explore the generality and boundary conditions of our findings. The quiet revolution of numerical weather prediction offers an exploratory proposal based on a single case, and further empirical testing against other similar cases and contexts would need to follow. In particular, it would be interesting to analyze additional cases where regeneration stands at the fore—where landscape pressure may very well exist, but where the problem of agency is even more pressing and problematic. As our study highlights, landscape pressure may undoubtedly serve a purpose, but there needs to be an element of agency for actors to sense and act on that pressure, and they must also act with some unity and direction in order to enable real transition.

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3. Interviews

Name	Institution	Location and date
Olivier Talagrand	CNRS–LMD	LMD, Paris, May, 2014
Jean Pailleux	Meteo-France and ECMWF	Paris, June, 2014
Philippe Courtier	Meteo-France and ECMWF	Champs sur Marne, June, 2014
Philippe Courtier	Meteo-France and ECMWF	La Défense, July, 2014
John Derber	NOAA/NCEP	By email July, 2014, and September, 2014, and at the ECMWF on September, 2014.
Olivier Talagrand	CNRS–LMD	LMD, Paris, September, 2014
Jean-Noël Thépaut	Meteo-France and ECMWF	ECMWF, September, 2014
Florence Rabier	Meteo-France and ECMWF	ECMWF, September, 2014
François-Xavier Le Dimet	Grenoble University and INRIA/MOISE	Grenoble, September, 2014
Philippe Veyre	Meteo-France and CNES	CNES, Paris, February, 2015

Philippe Courtier, researcher in NWP. Former PhD Student of Talagrand. Head of IFS/ARPEGE project at the ECMWF (during 1986–1988 and 1992–1996) and at Météo-France (1989–1991). PhD advisor (with Talagrand) of Thépault and Rabier.

John Derber, researcher, leading research scientist in charge of the implementation of variational data assimilation at NOAA/NCEP/Environment Modeling Center. His work led to the first operational implementation of 3D-VAR at NOAA in 1995, a few months before ECMWF. Close colleague of Talagrand and Courtier.

François-Xavier Le Dimet, Professor in Applied Mathematics at the University of Clermont-Ferrand until 1991, where he co-organized (with O. Talagrand) the first WMO conference on data assimilation. Then Professor at the University of Grenoble. Elected Fellow of the American Meteorological Association in 2012 for his pioneering work on variational data assimilation. Co-author with Talagrand of the fundamental 1986 paper on variational data assimilation.

Jean Pailleux, engineer in meteorology and expert in NWP and data assimilation at Météo-France until 1984. He then worked at ECMWF on data assimilation and satellite data until 1991, before returning to work at Météo-France on data assimilation for the IFS/ARPEGE project.

Olivier Talagrand, leading researcher on variational data assimilation. He was Head of the Scientific Council of ECMWF during the IFS-ARPEGE project, and was also Courtier's PhD advisor. He was awarded the Silver Medal of the French National Council of Scientific Research (CNRS) in 2004 for his pioneering work on variational data assimilation. Co-author with Le Dimet of the 1986 fundamental paper on variational data assimilation.

Jean-Noël Thépault, Former PhD Student of Courtier and Talagrand during the IFS/ARPEGE project. At the time of the interview, he was Head of the Data Assimilation Department at ECMWF. Co-author with Courtier of the paper on the incremental method that led to the implementation of 4D-VAR at ECMWF and Météo-France.

Florence Rabier, Former PhD Student of Courtier and Talagrand during the IFS/ARPEGE project. At the time of the interview, she was Head of ECMWF.

Philippe Veyre, Head of Quality Control in NWP at Météo-France during the IFS/ARPEGE project, where he worked on uncertainty in weather forecasting together with Courtier and Talagrand. At the time of the interview, he was Head of Weather and Climate Programs at the French Space Agency (CNES).

Glossary

4D-VAR: 4-dimensional variational assimilation. The latest assimilation technology at the time of our case study.

ECMWF: European Center for Medium Range Weather Forecast. A European for weather predictions and climate services. According to our interviews, the leading center in the world.

GPS-RO (for Radio Occultation): a technology using the deformation of a radio signal when it passes through the atmosphere to analyze its composition

LMD: Laboratoire de Météorologie Dynamique, CNRS, Paris. French oldest research center on meteorology.

NASA: US National Aeronautics and Space Administration, in charge of the development of research satellites

NOAA: US National Ocean and Atmosphere Administration, in charge of the exploitation of operational satellites.

NOAA/NESDIS: National Environmental Satellite, Data, and Information Service. Department of NOAA in charge of satellite, weather and climate prediction.

NOAA/NCEP: National Center for Environmental Prediction, Silver Spring, Maryland, USA. Department of NOAA/NESDIS in charge of NWP.

NWP: Numerical weather prediction.

OI: optimal interpolation. A mathematical technique of data assimilation.

OSIP: Operational Satellite Improvement Program. A joint NASA/NOAA program to improve the performance of weather satellite. Terminated in 1982.

Conflict of Interest

The authors have no conflict of interest.

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Research highlights

This paper reveals a new type of transition pathway, “regeneration”, in which the regime transforms itself from within, despite the lack of landscape pressure, to overcome internal tensions.

This paper identifies “project-oriented agency” as the central mechanism of this transition, which allows the actors to join forces and cooperate to counteract the reverse salient.

This paper proposes a process model of STT which accounts for the role of project-oriented agency in regeneration settings.