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Projects, Agency and the Multi-Level Perspective : Insights from Numerical Weather Prediction

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Abstract

This paper discusses the role of projects in technological transitions. Based on a case study of a technological transition in numerical weather prediction the paper discusses the multi-level perspective (MLP) framework developed by F. Geels & al. (2002 & next). This framework has been criticized for its macro-level perspective and its difficulty to deal with the question of agency. Our research suggests that the project level constitutes a promising avenue to discuss this question in the multi-level perspectives framework. It demonstrates how, in this case, a project play a major role in the transition from one technological regime to another and how at the project level actors can be included more precisely in the MLP. In so doing it also propose a type of transition, regeneration, not envisioned by the MLP research. Finally we suggest that bridging MLP and project management research, particularly contemporary works on innovative projects, could be fruitful for both fields.

Keywords: project, technological transition, multi-level perspective, agency, numerical weather prediction.

1. **Introduction**

There is growing interest in the field of innovation studies for the question of technological transitions. Indeed whereas most of the literature focuses on the design and diffusion of innovations, the question of transition from one technological system to another has recently gained a renewed attention. This is very probably triggered by the growing awareness that climate change will force our society to profoundly change their functioning in many domains (agriculture, transportation, energy, etc). In particular, the work of Frank Geels leads to an important research stream on the Multi-Level Perspective (MLP) framework (Geels, 2002 & next). The MLP represent the transition from one technology to another by the interaction between three different levels : the landscape, the current technological regime and niche in which radical innovations first appears. This frameworks leads to a renewal of the analysis of technological transition since it integrates scientific, technical, social and regulatory dimensions. Therefore the MLP sheds a new light on major technological transitions (e.g. from horse transportation to automobiles in Geels, 2005) and allows to identify different type of technological transitions (Geels & Schot, 2007). Of course the MLP is not without criticism (Smith & al, 2005 ; Genus & Cole, 2008). In particular a recurring question relates to the problem of agency and the relative lack of the actor's perspective in the MLP. Indeed, until now, research on MLP tends to favor longitudinal historical studies over a long time span. This perfectly sound methodological choice leads to relegate the actors in the background.

In this paper we wish to study this question of agency. We suggest that focusing on the project-level provide a fruitful avenue to discuss the question of agency in MLP. It could also constitutes a first step, as suggested by Geels (2011, p. 30) to bridge the MLP and business studies. This is all the more interesting that, as suggested by Engwall (2003), projects needs to be considered in their broader environmental and historical context. But the PM literature does not provide a model of the dynamic of the environment, particularly for innovative projects. Therefore we think that bridging project and MLP could be fruitful for both fields.

To do this we rely on a longitudinal case study of a technological transition in the field of meteorology. More precisely we will focus on the consequences of the introduction of satellite in earth observation systems. This, as we will demonstrate, generates major changes in numerical weather prediction (NWP). It took almost thirty years before the data generated by satellites leads to an improvement of NWP performance in the north hemisphere. Indeed this supposes a radical change in data assimilation methods (from the Optimal interpolation regime to the new 4D-VAR regime). These methods, as we will see, constitute a perfect example of *reverse salient* (Hughes, 1983). Overcoming this reverse salient needs both conceptual breakthrough in the mathematics of data assimilation and the setting of a project (named IFS-ARPEGE), jointly lead by the European Center for Medium-Range Weather Forecast (ECMWF) and Météo France, to implement this breakthrough. This ultimately leads to a global diffusion of this data assimilation method in most weather services. We thus propose that the project-level, which is present but not theorized in Raven & Geels (2010), may help to reinforce the agency dimension of the MLP.

The paper is organize as follows. The first section present the MLP discuss its limitations and propose that the project-level constitutes an interesting avenue for further research. Section 2 presents our methodology. In the third section the case is presented. Section 4 present the main result of the case. Finally section 5 discuss the implications for the MLP and project research.

2. Studying technological transition : the MLP and its limitations

The MLP has its roots in a group of Dutch researchers, the Twente school (Rip, Kemp and Schot) who build on evolutionary theory of economic change ant Science and Technology Studies (STS) to propose a global model that explain technological transitions (Geels, 2002 & next). The central concept of the MLP is the socio-technical regime, defined by Rip & 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 concept of technological paradigms (Dosi, 1988) or dominant design (Abernathy & Utterback, 1978) to take into account the rules and institutions that support a technology. The regime explains the stability of existing technologies and, therefore, the difficulty of radical innovations. In order to explains the emergence of radical innovations and the transition from one regime to another, the MLP introduce two other levels : the "niche-innovations" and the "socio-technical landscape" (see figure 1 below). The niche level is where the innovators and entrepreneurs develop radical innovations that challenge the existing regimes (e.g. automobile vs horse transportation). At the other end, the socio-technical landscape represents the exogeneous context where global societal trends may (or not) exert pressure on the existing regime (typically climate change that push toward renewable energies and cleaner modes of transportations). With the three levels at hand, research on the MLP provides an extremely fruitful framework to study technological transitions. For example Geels (2005) demonstrates the great complexity of the transition from horse-drawn carriage to automotive and Geels & Raven (2006 & 2010) compare the trajectory of Netherlands and Denmark in biogas development.

The great strength of the MLP is twofold. First it integrates a wide body of literature in innovation management within an evolutionary-based framework. Second, in so doing, it encompasses technical, sociological, legal and institutional factors, which allows them to provides rich, multi-dimensional case study. Moreover, whereas in a first period the MLP clearly favored a bottom-up approach in which innovations comes first and foremost from niches (the Strategic Niche Management perspective, see Raven, 2005), latter research build a typology of transition trajectories (Geels & Schot, 2007) in which the interplay between the three levels is much richer. This, depending on the timing of the interactions between landscape pressure and niche-innovations (are they mature enough or not ?) and the nature of this interactions (do they reinforce of disrupt the regime ?), leads Geels & Schot define 4 transitions pathways[1] : (1) *technological substitution, based on disruptive niche-innovations which are sufficiently developed when landscape pressure occurs, (2) transformation, in which landscape pressures stimulate incumbent actors to gradually adjust the regime, when niche-innovations are not sufficiently developed, (3) reconfiguration, based on symbiotic niche-innovations that are incorporated into the regime and trigger further (architectural) adjustments under landscape pressure, (4) de-alignment and re-alignment, in which major landscape pressures destabilize the regime when niche-innovations are insufficiently developed; the prolonged co-existence of niche-innovations is followed by re-creation of a new regime around one of them*" (Geels & al, 2016, p. 896).

Of course, as deserve all landmark contributions, the MLP has been subject to different criticism (Smith & al, 2005 ; Genus & Cole, 2008 and table 1 below) which concern both the methodogy, the epistemology, the definition of the different levels and representation of agency in the MLP (see Geels, 2011). In this paper we want to focus on this last critique.

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[1] Actually 5 pathways, the last one being a combination of the 4 pathways.

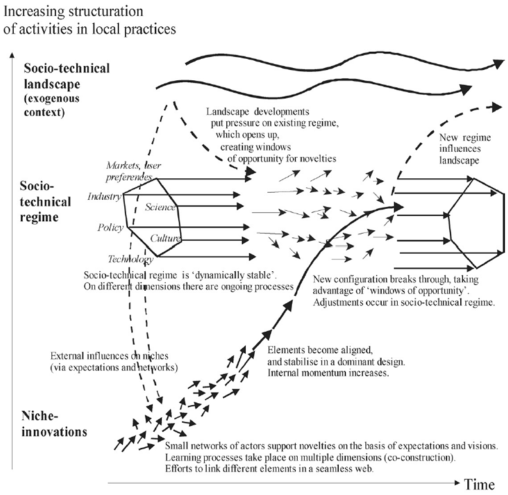

Figure 1. The Multi-Level Perspective (from Geels, 2002)

Indeed both Smith & al. (2005) and Genus & Cole (2008) argues that the long-term and macro historical case studies typical of MLP research downplay the role of agency and of the actors involved in the transition process. This points is acknowledged by Geels & Schot (2007) who recognized that " *does not always comes through strongly in stylized case-studies and figures*" (p. 414). This, they say, is probably due to the fundamental nature of the MLP which is a "*global model that maps the entire transition process*" (ibid). And actually the preferred approach of MLP research is historical case study over long time span, which is completely coherent with their object since transition typically took decades to happen. However it is fair to say that the MLP does not ignore agency. Three points are worth noting. First F. Geels devotes considerable time to explain the type of agency underlying the MLP (Geels & Schot, 2007). In particular Geels (2010) explains at length how the MLP accommodate different ontologies of agency (rational choice, structuralism, and so on). However this answer remains mainly theoretical and far from the actor's practices that are almost absent from MLP case studies. A second avenue is provided by Schot & Geels (2008) which insist on the fundamental role played by projects and sequence of projects, particularly at the niche level that "ma*y gradually add up to an emerging field (niche) at the global level*" (p. 543) finally leading to a regime transition. Raven (2005) and Raven & Geels (2010) demonstrates the fruitfulness of this approach by studying the succession of (successful and unsuccessful projects) in the case of biogas development in the Netherlands and Denmark.

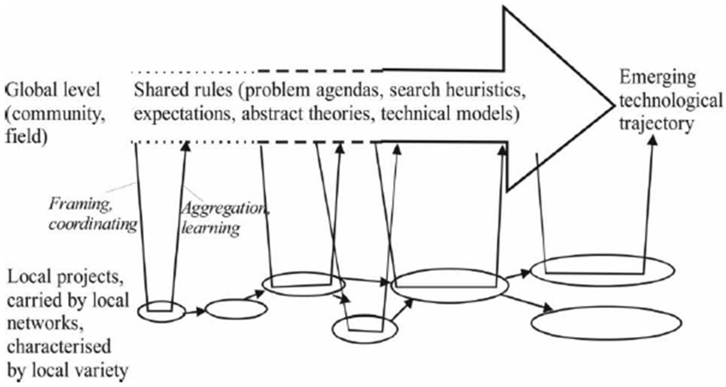

Figure 2. The role of local projects (from Schot & Geels, 2008, p. 544)

However here again MLP research remain quite far away from the actor's practices in projects. This is, in our view, partly unavoidable since it is very difficult to study regime transitions that span decades and to conduct a [micro]-analysis of project unfolding. But we believe that MLP could benefit from a project perspective. This is in accordance with Geels (2011) who suggests that in order to better integrate actors "*the MLP could benefit from stronger incorporation of insights from business studies and strategic management*" (p. 30).

Indeed the project seems a promising unit of analysis to study agency. It constitutes a middle-level between actors and the regime. Moreover history of innovation demonstrates the central role played by the project from or organizing in the emergence of new technology and infrastructure (see Hughes, 1998). Projects may serve as "*sheltered places*" to experiment and demonstrates new technology (Raven & Geels, 2010) and, as we will see they can also play a central role in the transition process from one regime to another.

Our aim in this paper is to follow this pathway by showing how projects can play a crucial role in regime transition. To do this we will adopt the perspective proposed by Engwall (2003) who forcefully demonstrates that projects are not island. To understand their unfolding we have to analyze them in their broader environment and historical context. However we will suggest that the reverse is also true : projects may trigger important change in their environment contributing decisively to regime transition. We now turn to this question

3. <u>Research design and data</u>

3.1. Context : meteorology and satellites

This work is part of an ongoing collaborative research with the french space agency, the Centre National d'Etudes Spatiales (or CNES). It started in 2010 on the question of innovation processes within the CNES in the domain of earth-observation (EO). Today EO satellites have a broad array of applications, from the images that illustrates google earth (and were first designed for military surveillance) to climate monitoring, operational oceanography and weather prediction. In 2014 this leads us to focus more precisely on the value and uses of space data, a recurring problem in the space industry (Courrain, 1991; NRC, 2003). To do this we focus on the case of meteorology. Indeed, today, weather satellites provides almost 80% of the data used in numerical weather prediction systems. But, as we will see, this hides a long struggle to use effectively the data produced by weather satellites. More precisely, and this is why this case is so interesting, using the space data triggers a regime change in numerical weather prediction.

3.2. A short introduction to NWP and data assimilation

In order to understand the problem, a short detour by the functioning of numerical weather prediction is needed. A NWP model is a complex machine that is based on the physics of the atmosphere and needed an immense amount of data to function properly (1 billion, today at the ECMWF). Indeed NWP is as explained by Kalnay (2003), NWP is an initial value problem since a small mistake in the initial conditions can have a huge impact on the quality of the forecast[2]. Therefore a forecast is a two-step process. The role of the first phase, named data assimilation, is to use "*all the available information* [from balloons, ground stations, satellites, etc] *to produce the most possible accurate description of the state of the flow, together with the uncertainty resulting from uncertainties on the various sources of information*" (Talagrand, 1997). On this base starts the prevision itself. This cycle is repeated at least two times a day. It is extremely complex because of the huge dimension of the problem and the "*non-trivial, actually chaotic, underlying dynamics*" of the physical processes at stakes (Talagrand, 2014). Consequently, and since their creation, weather services are lead users in the domain of supercomputing.

Concerning our research question, the most important step is data assimilation. To understand the problem one has to know that there exist much less observations, than gridpoints in the model (aprox. 1 obs for 100 gridpoints). This explains why, in order to determine the initial conditions, meteorologists rely on complex techniques that combine observations and the preceding forecast as a "first guess". Until the 80's and early 90's the "*operational analysis scheme of choice* » was Optimal Interpolation (OI) (Kalnay, 2003, p. 150). In OI the values at

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[2] Chaos theory has its roots in NWP with the famous question raised by E. Lorenz in a 1971 conference : « *Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?* »

missing gridpoints were approximated by statistical techniques from information available in the neighborhood of the gridpoints[3].

3.3. Data collection and analysis

Data collection was performed over 12 month from may 2014 to may 2015. Our goal was to understand the process that explains the difficulty of using radiances in NWP and how this problem was finally overcome, leading to a revolution in NWP. Therefore we adopted the strategy of process research which seeks to make sense of the collected data to understand the unfolding of a process over time (Langley, 1999 ; Yin, 2003 ; Langley & al, 2013). This is in line with MLP research which "*employs 'process theory' as explanatory style rather than 'variance theory'*" (Geels, 2011). To build our case study we rely on three source of evidence (All these sources are presented in the appendix) :

1. The existing literature on meteorology and its uses of space technology that exist in history and Science and Technology Studies. The book from Conway (2008) triggers our curiosity by pointing the conflict between NASA and NOAA around the use of satellite data in NWP. M. Courrains Ph D (1991) provides a vast amount of data on the use of remote-sensing data in weather prediction. Research by Krige (2000) and Edwards (2010) helps us to understand the problem at stakes. We also rely on the US National Research Council reports on the operational use of space data, which constitutes a recurring problem since at least 20 years (NRC, 2000 & 2003) ;
2. Our second source of evidence comes from the scientific literature in meteorology. Since the problem leads to a vast amount of research over at least a decade it was interesting to exploit this literature in order to understand the problems at stake but also to get a minimum level of expertise for the interview with the actors. Moreover the peer-reviewed literature allows us to cross-check the interview, track the debates in the meteorological community, verify the dates, etc. ;
3. Finally we conduct interview with the main actors involved in this process. 10 interview with 8 of the key actors involved in this transition were interviewed between may 2014 and September 2015. All the interview were recorded and then transcribed. This interview allows us to understand the processes at stakes and the unfolding of the project. They were completed by follow up email our phone conversation when necessary.

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[3] Our goal is not to expose OI. The interested reader could refer to Talagrand (1997) or Kalnay (2001).

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 he richness, dynamism, and complexity of the data but that is understandable and potentially useful to others*" (p. 694). Our process starts we the narrative strategy described by Langley which "*involves construction of a detailed story from the raw data*" (p. 1999). It takes the form of a research report for the CNES (Lenfle, 2015) that contains a detailed, 70 pages, case study of the uses of radiance in NWP. This report was sent to the informants, read and annotated by some of them. Latter, in a second step, we also rely the visual mapping strategy to synthetize the data and get a better understanding of the transition process (see section 5). Finally the report leads to a first peer-reviewed publication in *La Météorologie*, the review of the French meteorological society (Lenfle, 2018). This research strategy allows us to probe deeply into the processes at stakes in regime transition. We now turn to the case, relying on MLP concepts to structure the story

4. <u>From optimal interpolation to 4D-VAR data assimilation : the "*quiet revolution*" of NWP</u>

4.1. The regime

To understand the problem we first have to present shortly meteorology and numerical weather prediction. The development of weather prediction dates back to the middle of the 19th century. After the destruction of part of the French fleet in the black sea on may 14, 1854, Urbain Le Verrier decided to create the first weather observation network. Almost a century later, weather prediction makes an outstanding demonstration of its military significance on the D-day (Nebeker, 1995). This leads first to a continuous expansion of the uses of meteorology over the next decades. For our research three points are worth noting :

1. After World War II the possibility to forecast the weather becomes a major research question following the advent of the electronic computer. Thus John Von Neumann considered that meteorology was one of the major applications of computing and, when he launched his Electronic Computer Project at Princeton in 1946, it includes a "Meteorological Research Project" led by Junes Charney, who will become a major figure of NWP. This will lead, 8 years later, to the first operational weather prediction in Sweden in 1954, then in the US in 1955. The story of the rise of NWP is now well documented (Nebeker, 1995 ; Fleming, 1996 ; Kalnay & al, 1998 ; Harper, 2008). It shows the incredible improvements of NWP

performance over sixty years to near perfect 3 days forecasts nowdays. Today it constitutes an essential tool of weather services around the world.

2. Under the coordination of the World Meteorological Organization (WMO created in 1950 as an agency of the UN) meteorology created a very large technical system. The World Weather Watch[4] (first www, created in 1963!) is now an extremely complex observation network that collect billions of information each day through ground stations, balloons, buoys, plane, boat, and, since 1969, satellites, telecom facilities, and data processing centers. P. Edwards (1996) coined the term *infrastructural globalism* too qualify this huge, truly global, and highly standardized system that lay behind our daily weather report.
3. Consequently we observe a symmetrical expansion of the uses of weather forecasts. It is used first by public authorities to predict the weather, particularly extreme events like storms and floods. But we also observe the rise of commercial meteorology since many industrial sectors (energy, transportations, agriculture, leisure…) are directly influenced by the weather (see Randall, 2010). Hence the socio-economic benefits of weather forecasts are estimated at €15billions per year for UE27 at minimum (with likely benefits of €61billion/year[5]).

Weather satellites have had an important role in these evolutions. Since the launch of Tiros-1, the first weather satellite, by the NASA in april 1st, 1960, space system have become an essential component of the World Weather Watch. They provide images of the cloud cover as well as numerous indispensable data for NWP models. Here we will focus on what is called satellite sounders. These are instruments that, through highly complex sensing systems, measure radiances in the atmosphere. From these radiances it is possible to calculate temperature, one of the most important variable in MWP models. Traditionally temperatures in the atmosphere were measured with weather balloons which provided very precise temperature profile at a precise location. This technique had of course a major drawback : its limited coverage. Therefore scientists decided to see if satellite could provide an alternative solution. Therefore the first sounder, SIRS-A, was launched in 1969 on the Nimbus-3 satellite[6]. Howeverthe use of the radiances produced by satellite sounders proved to be extremely difficult. This leads to important debates and conflict in the US and the weather prediction community on the utility

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[4] More information here http://www.wmo.int/pages/prog/www/

[5] See : http://www.wmo.int/pages/prog/sat/meetings/documents/PSTG-3_Doc_11-04_MetOP-SG.pdf

[6] It is out of the scope to study the origins and design of this instrument. The interested reader could refer to Conway, 2008.

of these data. Almost thirty years were necessary to demonstrate their positive impact of on the performance of NWP in the north hemisphere[7] (Derber & Wu, 1998). In the meantime a "quiet revolution" (Bauer & al., 2015) occurred in NWP to handle these data. As we will see the regime of NWP changed radically particularly in the fundamental domain of data assimilation.

4.2. Tensions and misalignments

4.2.1. The emergence of weather satellites

The idea of using satellite for meteorology is as old as the satellite themselves (RAND, 1946). In the 50's the possibility of "weather reconnaissance" was discussed in a famous RAND Corp. report (RAND, 1951). This leads to the launch of the first weather satellite, TIROS-1, in 1960 which provided the first images of the cloud cover. The advantages of satellites were obvious since they provided a global coverage of the earth. However it took almost 10 years to use the image in daily weather forecast ven if they proved quickly very valuable to predict extreme events like hurricanes over the north Atlantic (Courrain, 1991). But these images were useless (and still are) for numerical weather prediction which rely on physical parameters. Therefore, in the 60's, scientists at NASA had the idea to use the instrument designed to explore other planets to study the earth atmosphere (Conway, 2008). This leads to the launch of the first satellite sounder, SIRS-A[8], on the Nimbus-3 R&D satellite in april 1969. The results were promising enough to launch a series of research instruments (SIRS-B in 1970; IPTR in 1972,…) that finally leads to an operational instrument, HIRS-2, launched on TIROS-N in October 1978. This satellite provides data on temperature and humidity over the earth. They were the first to be considered reliable enough by meteorologist to be included in their operational weather prediction models. And this is where problems begin.

In 1979 the Global Weather Experiment conducted as part of the Global Atmospheric Research Program integrates the satellite data. The results were disappointing, to say the least. They show that much of the improvement in weather forecast were due to better models, not to satellite data (Edwards, 2010). Worst, these new data leads to a deterioration of the forecasts. This problem was confirmed by Tracton & al. in a 1980 paper which demonstrates that the impact of remote satellite data on NWP in the north hemisphere was "negligible". This triggers a fierce debate within the meteorological and space communities. It was especially virulent between NASA, in charge of the development of new instruments and research satellite, and NOAA, in

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[7] Which represent 2/3 of the land and 90% of the earth population.

[8] For Satellite Infrared Sounder.

charge of operational satellites, numerical models and weather forecasts. It came to a point "*when NOAA/NESDIS had sent over to NASA requirements for a next-generation sensor and the model developers at the NWS*[9] *had refused to verify them. Indeed, they took a position of rejecting the value of satellite data entirely. Because the satellite data did not produce better forecasts than the radiosondes, 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. So NASA and NOAA leaders agree to end the Operational Satellite Improvement Program*[10] *in 1982*" (Conway, 2008, p. 91, emphasis is ours). The consequence were straightforward: this froze the design of new instruments and leads to « *a two decade long hiatus in new instruments for the polar orbiters* » (ibid.) Therefore "*the instrument generation of 1978, with only minor updates, continued to fly through the end of the century*" (ibid. p. 92). Thus meteorologist had to wait until december 1998 to see an improved version, HIRS-3, and 2002 to benefit from a real breakthrough in instrument, AIRS.

4.2.2. Assimilating radiances, first try : the satellite-to-model approach

The first solution used by meteorologists to handle the new satellite data was to make them compatible with the existing operational methods. This cannot be more clearly stated than by the director of forecast at the NOAA who said in 1969 that "*If you can make them look like radiosonde data we can use them*" (quoted in NRC, 2003, p. 102). A. Hollingsworth (1990), a famous expert of NWP at the ECMWF, called this approach « *satellite-to-model* », since the goal was to force the data to be compatible with the existing assimilation techniques. But, as said above, the results were disappointing. Scientific articles show that satellite data did not improve the quality of the forecast. Worse, in a 1991 paper (10 years after Tracton & al.), Anderson & al demonstrates that the impact of satellite data has turned from negligible to negative. Actually the 80's were a period of great disappointment for meteorologist. As explained by Ph. Courtier, "*This is terrible to know that satellites were the future of meteorology but that we were unable to use the data efficiently*" [PhC1][11]. Actually different problems overlap to explain these disappointing results.

The first problem comes from the data themselves. Indeed satellites sounders did not measure the temperature of the atmosphere. What they measure are radiances that are indirectly linked

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[9] The National Weather service, of the NOAA, in charge weather prediction.

[10] OSIP's role was to improve satellite performances and facilitate the transition from research to operations.

[11] All the quotation in [ ] refers to the interviews. See the appendix.

to temperature (and many other variables like humidity) through a complex physical function called the radiative transfer equation. However if this is relatively easy to deduce radiances from temperature and humidity, the reverse is not true. This leads the NOAA to design complex mathematical procedures called “retrievals”. This leads to “pseudo-soundings” called SATEM by the NOAA. They look like radiosonde data and were assimilated in NWP. However they were actually of very bad quality compared to radiosonde soundings with “ *only three points in the atmosphere.*” [JP]. This is the first reason why the assimilation of this poor information in ever complex models leads to the degradation of the forecasts. The consequences were straightforward. As Woods (2006) explained in his history of the ECMWF, in the 80’s “*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 not just being used optimally. Something needed to be done here, but it was not clear just what*” (Woods, 2006, p. 94). What has to be done comes from a research stream on alternative assimilation methods.

4.3 Emergence of new Concept : “variational” assimilation

The necessity to do “retrieval” was not the only limitation of optimal interpolation. It was well known by researchers in meteorology that OI had severe limitations to handle uncertainty. As O. Talagrand, a leading researcher in data assimilation, explains “*one of the main problem in NWP is to know how the atmosphere evolves over time but also how the associated uncertainty evolves and OI did not handle this question*” [OT2]. This explains the growing gap between the initial condition determined by OI and the need of the model. This question leads to an important research stream on alternative assimilation methods. In France in particular Olivier Talagrand, well aware of the limitations of OI, was looking for other methods (Talagrand, 1981a&b). Independently, a french applied mathematician, FX Le Dimet was studying the potential of “variational” methods for assimilation. The roots of this variational approach was actually old. It dates back to the work of Y. Sasaki, a meteorologist from the University of Oklahoma who propose this approach in 1955 and published several papers in 1970 (Sasaki, 1970a, b & c). In this approach the statistical methods of optimal interpolation were replaced by the minimization of a cost function that represents the gap between the initial conditions of the model and the available information. This minimization can be done at a given point in time (3D-VAR) or, on a more elaborate version, over a time windows in order to optimize not only the initial conditions, but the trajectory of the model (4D-VAR). However this remains mainly theoretical without any impact. Nevertheless, in 1982 FX Le Dimet, goes to work with Sasaki in Oklahoma. His question was to know if the mathematical techniques of optimal control, of which he was an expert, could be applied to the variational problem. Using optimal control to solve meteorological problem was a very innovative idea. This leads to a first draft of a paper submitted in 1982 to a leading scientific journal and rejected. Then come a decisive meeting. In 1983, during a congress of the French physic society FX Le Dimet met Olivier Talagrand. Talagrand's mathematical background was solid enough to understand the work of Le Dimet and he has already heard of variational methods through his contact with Russian mathematicians. Le Dimet proposal to use the so-called *adjoint equations*[12] allows, for the first time, to minimize the cost function of the variational method. This meeting leads to a breakthrough paper published in *Tellus* in 1986 (Le Dimet & Talagrand, 1986)[13]. This paper unlock the variational method and leads to a sudden growth of research on variational assimilation at the end of the 80's – early 90's (see Courtier & al, 1993). It is interesting however to note that, at this time, research on variational methods had nothing to do with satellite data. Le Dimet & Talagrand were much more interested by the dynamic treatment of uncertainty than by the assimilation of satellite data.

Immediately after the 1986 paper O. Talagrand start to explore the operational potential of variational assimilation with a Ph D student, Philippe Courtier. Coutier's Ph. D (1987) and the associated papers (Talagrand & Courtier, 1987 ; Courtier & Talagrand, 1987 ; Courtier & Talagrand, 1990) demonstrate the potential and feasibility of variational assimilation on simplified models. The problem became so important and the potential of variational assimilation so significant that the ECMWF and Meteo France[14] decided to join their forces and to launch a project, called IFS/ARPEGE to implement the method. Shortly after this decision Le Dimet & Talagrand were contacted by the World Meteorological Organization to organize the first world conference on data assimilation. It was held in Clermont-Ferrand (France) in july 1990 with the main members of the assimilation research community .

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[12] On adjoint equations see Errico (1991)

[13] "Variational Algortithms for Analysis and Assimilation of Meteorological Observations: Theoretical Aspects", 1781 quotation as of May 31, 2018.

[14] The French weather service.

4.3. Tipping to the variational regime : the IFS/ARPEGE project

4.3.1. The road to implementation.

IFS/ARPEGE was a huge challenge. In 1988, many people doubts that the technique was feasible. Four problems will have to be solved. The first one, is theoretical. The methods of optimal control had never been used operationally on huge and non-linear numerical models. Second, and this was probably the most important problem, variational methods required a huge amount of computing power[15]. Le Dimet is crystal clear on this question : "*when we publish the first papers this was absolutely impossible*. (…) *you have to put this in perspective with the evolution of supercomputers. Otherwise this had no meaning. Without this, this was a very bad idea*" (FXLD). The problem is all the more complex that NWP models themselves are also consuming more and more computing power. Third was the immense task of integrating the new methods in operational systems. Indeed NWP in meteorological services really are data plants. This supposes to respect very strict requirements in terms of data quality, data transmission, computing, speed, etc. One particular problem was to develop what is called the "adjoint model". According to Talagrand "*this was completely new. Until now people using adjoint methods create the model and its adjoint simultaneously. Here the problem was to design the adjoint of a huge model that already exists. Apparently, nobody ever done that*" [OT2]. Last, but not least, was the question of radiances. Even if assimilating radiances properly was not the main reason to launch the project, the question soon became central. Indeed, the coverage provided by satellites remains a breakthrough innovation for meteorologists. This four challenges explains the joke of FX. Le Dimet during an interview : " *Had I know* [in 1982 – 1983] *what it cost* [in computing power] *I would have given up immediatly* [laugh]!! *We didn't suspect the difficulties* [of operational implementation]" (FXLD).

4.3.2. The sweat and tears (1) : computing power

According to Andersson & Thepaut (2008), who were both key figure of the project, IFS/ARPEGE was "*One of ECMWF's biggest-ever projects*". Indeed the project mobilized around 30 people during 10 years and most of the PhD students worked on the project. According to Thepaut, "*this was a gigantic endeavor, we had to develop everything from the adjoint models to the handling of satellite data*" (JNT). Furthermore this was a very risky decision: "*you had to be visionary because when Talagrand & Courtier published their 1990*

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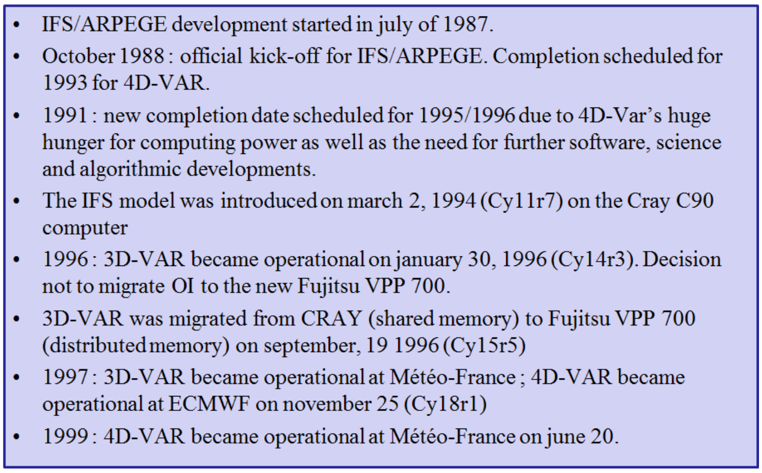
[15] "B, for example, is a matrix of size 10^7 x 10^7 which is about 1000 times the total archiving capacity of ECMWF and one million times the memory size of current computers" (Courtier, 1997).

paper, the computing power was not available.” [JNT]. Philippe Courtier, whom we’ve already met, was unanimously recognized as the driving force leading the project. A pioneer of variational methods he plays a central role in the project at the ECMWF (in 1986 -88 and 1992-96) and at Meteo-France (1989-1991). In particular Courtier brings together the three expertises of data assimilation for NWP, mathematics of optimal control and computing.

The project starts in the summer of 1987 (see figure 4 for the main dates). The first task was to recode the prediction model since it was incompatible with variational methods. This took two years since the team take this opportunity to change the architecture of the code in order to make it modular and more flexible to future evolution. After this first phase, the team turns back to the design and implementation of variational data assimilation. They soon realize that they had underestimated the amount of work. Thus, in 1991, the completion date was postponed to 1995/96 instead of 1993, as it was originally planned.



- IFS/ARPEGE development started in july of 1987.
- October 1988 : official kick-off for IFS/ARPEGE. Completion scheduled for 1993 for 4D-VAR.
- 1991 : new completion date scheduled for 1995/1996 due to 4D-Var’s huge hunger for computing power as well as the need for further software, science and algorithmic developments.
- The IFS model was introduced on march 2, 1994 (Cy11r7) on the Cray C90 computer
- 1996 : 3D-VAR became operational on january 30, 1996 (Cy14r3). Decision not to migrate OI to the new Fujitsu VPP 700.
- 3D-VAR was migrated from CRAY (shared memory) to Fujitsu VPP 700 (distributed memory) on september, 19 1996 (Cy15r5)
- 1997 : 3D-VAR became operational at Météo-France ; 4D-VAR became operational at ECMWF on november 25 (Cy18r1)
- 1999 : 4D-VAR became operational at Météo-France on june 20.

Figure 4 : Main dates of the IFS/ARPEGE project (from Andersson & Thepaut, 2008)

The problem comes from computing power needed for variational assimiliation. This question was central in the debates between the supporters and opponents of the variational approach. Indeed, given the very strict requirements of operational weather prediction, the time windows for the forecast cycle is very short (2-3h) whereas variational assimilation increased the computing cost by a factor of 100. This was the main argument of the opponents of the method. The breakthrough comes in 1992-93 in a conversation between Courtier, Thepaut and John Derber of the NOAA who, a this time, was at the ECMWF. This leads to the development of a cost-saving method, the “incremental approach”, published in 1994 (Courtier & al., 1994). It allows a tenfold reduction of the computing cost which “*de facto render the 4D-VAR feasible on ECMWF supercomputer*” (JNT).

4.3.3. The sweat and tears (2) : assimilating radiances, final push.

However the story was not over. Indeed, even if this was not the justification for the project, the assimilation of radiances became a central 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 & al, 2014, p. 25). The rise in importance of this question is obvious in the proceedings of the WMO Clermont-Ferrand conference. In his opening conference A. Hollingsworth, head of research at ECMWF, (Hollingsworth, 1990) distinguishes two approaches to handle these data : "satellite to model", based on optimal interpolation and "retrievals" and the new variational "model to satellite" which he said « *has still to be tested in real size problems* ». The terms used by Hollingsworth are worth noting since they summarized the complete reversal that occurred during the transition from OI to 3D/4D-VAR. Indeed in the variational approach the process starts from the forecast model to calculate radiances. Then these "model radiances" are compared to the real radiances as measured by the satellite. The variational algorithm then modify "model radiances" to make them as close as possible to the real one. Thus the complex retrieval process, with all its approximations, disappeared. But this was theoretical in 1990. The work on radiances was lead by J. Eyre and JN Thepaut[16]. It proved to be excessively difficult given the complexity of the algorithms and of the physical processes at stakes. Without going into the detail it is interesting to relate an important episode that takes place in 1993. At this date most of the work has been done : thanks to the incremental approach, the variational process works and is tested extensively before moving to the operational phase. But the results from the assimilation of radiances remain disappointing, without much effect on the accuracy of the forecasts. During a brainstorming session, Ph. Courtier understood that the problem comes from the fine-tuning of the so-called background error covariance matrix, which is excessively complex and plays a central role in forecast accuracy. God's in details…

4.4. The spread of the variational approach

This impressive work leads to the implementation of the variational approach at the ECMWF in January 1996 for the 3D-VAR, just one month after the NOAA where a team lead by John Derber launch it in December 1995. But this was just the first step and just one year later, in 1997 the ECMWF moved to 4D-VAR, the ultimate goal of the project. Meteo-france followed with 3D-VAR in 1997 and 4D-VAR in 1999. The results were so spectacular that this triggers

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[16] JN Thepaut started his Ph. D under the joint supervision of O. Talagrand & Ph. Courtier in 1988 and plays a key role in the implementation of 4D-VAR at the ECMWF and Meteo-France. When we collected the data he headed the "data division" of the ECMWF.

a worldwide diffusion of variational assimilation. ECMWF and Meteo-France were thus followed by the UK Met Office in 2004, both the Japan Meteorological Agency and Environment Canada in 2005 and the US Naval Research Laboratory in 2009 (Bauer & al, 2015). All the leading weather forecast centers in the world have adopted variational assimilation. Indeed the new approach proved to be "*a systematic method to introduce any kind of data in the assimilation process*" (OT2). For example the GPS Radio Occultation (or GPS RO) data have been assimilated in the late 90's into NWP. This explains why, 20 years after its first implementation the IFS/ARPEGE code and the variational scheme are still in use today at ECMWF and Meteo France, a dazzling proof of its power and resilience.

5. Results : from OI to 4D-VAR, Discussing the MLP

The story of the transition from optimal interpolation to 4D-VAR in numerical weather prediction represents an interesting case to discuss the multi-level perspective. In this section we want to emphasize three contributions: the originality of the case, its relation with the typology proposed by Geels (2007) and the relevance of the project level to study agency in the MLP.

5.1. NWP as a regime transition

The first contribution of this research is empirical. Indeed we believe, following here Flyvbjerg (2006), that cases have value in and of themselves and that building a database of cases is fundamental in theory building. Therefore, the NWP case enrich the database of MLP and technological transition research. In this perspective it present two original characteristics compared to the existing MLP literature :

1. Weather centers are producing information, not goods or energy. More precisely the world weather watch produces environmental information. Thus it constitutes a very interesting case to the extent that this kind of systems are playing and will play an fundamental role in the future to monitor and adapt to climate change. How this system function and how they evolve is an important area of research ;
2. It allows us to study the unfolding of transition in a global technico-scientific network. Indeed, meteorology is the first truly global system since it connects measurement instruments and weather centers[17] all over the world. Furthermore weather prediction is

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[17] Weather centers constitutes the archetype of B. Latour calculations center. In a 1996 paper he uses a weather map produced by meteo-France to illustrate the activity of calculations centers.

a science-based activity. Models are continuously evolving to integrate the last advances of research in atmospheric science and supercomputing. Thus the weather centers have a dual operational and research mission which are closely connected. This, as we will see, explains some of the characteristics of regime transition.

This allows us to test the relevance of the MLP's concept in a new empirical context. And relevant they are. Indeed the organization of meteorology really corresponds to the notion of regime as defined in the MLP. It combines technical (measurements instruments, computers, telecommunication systems), organizational (the WMO, weather services, research centers, private firms) and intangible elements (rules of the WMO, knowledge on NWP, knowledge on assimilation, etc.). Moreover, given the requirements of weather prediction, it is also extremely standardized : the type of measurements, instruments, location, hour of measurement, etc are defined by the WMO to guarantee the quality of the information on which forecasts are based. We can thus expect a great inertia of the system. In this case the landscape refers to the needs and expectations of society regarding weather prediction, the regime is the complex networks of observations systems, calculations centers, global organization that produces weather predictions, and the niches are the research centers (some having also an operational role) and other actors that try to improve the system.

The interesting point in this case is that we are able to characterize precisely the nature of the transition. What we observe here, as shown in the case, is a regime transition triggered by tensions on the modelling of uncertainty and by the arrival of radically new measurements instruments, satellite sounders,What is striking in this transition is length of the process, and the fact that it took almost 20 years to overcome the system reverse salient (Hughes, 1983) : data assimilation. Figure 4 below summarize the difference between the two regimes. It underlines that the transition was not only technical, it also concern the "intangible elements" of the regime, in this case the conceptual breakthrough represented by the use of the mathematics of optimal control to overcome the limitations of optimal interpolation. We now turn to the analysis of the process leading to this transition.

	Traditional/OI regime	**Variational regime**
Measurement instruments	In-situ (buoys, ground stations, balloons, boats, etc.)	In-situ and remote sensing (including satellites)
Nature of measurements	Conventional : direct and synoptic[18]	All including indirect and asynoptic.
Assimilation methods	Optimal interpolation	3D / 4D-VAR
Theoretical background	Statistical estimation	Optimal control

Figure 4 : From OI to 4D-VAR, a regime transition

5.2. Transition from OI to 4D-VAR : transformation, reconfiguration or regeneration ?

Now what does this case teach us on the unfolding of the transition process ? How does it fit with the typology of transition pathway proposed by Geels & Schot (2007) ? Indeed one of the critics addressed to the MLP was to be excessively bottom-up : radical innovations were first developed in niches before modifying the regime when landscape pressures becomes strong enough. Therefore the Geels & Schot 2007 paper constitutes a significant contribution. They identify 4 different pathway (see section 2). The fundamental logic of the framework is that the transition depends on the interaction between landscape pressures and the "readiness" or timing of the niches. More precisely this typology makes two important contributions. First it distinguishes different types of transitions based on the speed of these changes. Second the relations between the different levels of the framework are more complex and niches did not necessarily play the primary role.

Compared to these 4 pathway our case present several specificity. First it is very hard to identify some kind of "landscape pressure". As noted in the figure 6 there is no shock or radical change or even a slow one. What we observe is a typical sustaining trajectory (Christensen, 1997) : a continuous demand for more precise forecast and an extension of the uses of meteorology. But we can't identify some pressure for changes in meteorology at the landscape level. However we can identify "tensions or misalignment" (Geels, 2004) in the regime. We see 4 of these :

1. A scientific dissatisfaction with the current assimilation techniques concerning the handling of uncertainty (Talagrand) ;
2. A growing gap between the needs of the models and the performance of optimal interpolation to determine the forecast initial conditions ;

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[18] At fixed hours.

3. A stagnation of the performance of NWP at the ECMWF (and probably other weather services).
4. The inability to use satellite data efficiently. This is a problem that becomes more salient in the late 80's - early 90's when satellites launch, not necessarily for meteorology, multiplies ;

The fourth of this tension was, in a way, external, since the first satellite was launched by NASA to experiment space sounders on earth atmosphere. However this quickly became an internal problem since the instruments were launch on NOAA satellites, NOAA being a key actor of weather prediction. This sudden entry of a new type of instruments is partly responsible of the transition under study. For the three other tensions, it is difficult to say that they were "external". They really comes from within the regime and were expressed by researchers who were very knowledgeable about operational weather forecast, or by forecaster in charge of operation with a research background. Ph. Courtier is typical of this: when he was working on his PhD on variational methods, he was operationally in charge of optimizing the optimal interpolation algorithm[19]. In other word, the tensions here come from within the regime. The most "external" influence in our case comes from FX Le Dimet who is the sole actors who does not work in a meteorological lab but in applied mathematics. However this is where the conceptual breakthrough comes from. In the same vein it is difficult here to clearly identify niches were innovations were first developed. What we see are experiments, first in research centers but quickly in the research departments of operational centers, on simplified models to demonstrate the potential of the variational scheme. But this cannot be considered a fully developed innovation. The gap to an operational system is, as we have seen, absolutely colossal. And the problem is that supercomputing constitutes a bottleneck: to implement an innovation in NWP you have to demonstrate in real conditions that it is better than the existing regime. And real conditions are possible only in the few weather centers that have the computing power. In a way the niches are the fundamental research centers on meteorology, first and foremost the Laboratoire de Metéorologie Dynamique in Paris. But they are not alone to work on the question since the operational centers also have a research department.

Therefore what we see here is a regime transition that resemble the reconfiguration pathway but with tensions that comes from within the regime and innovations that were not symbiotic. Indeed, the zooming on the actors level make the notion of "local problem" quite complex.

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[19] The same is true for Jean Pailleux and Olivier Talagrand.

Indeed introducing a new data that requires a radical change in data assimilations method is not, as demonstrated in section 4, a “local” problem. It requires a complete redesign of the entire system. The figure 6 , based on the categories of the MLP, gives an overview this process. Schematically we distinguish 4 phases.

A. The process starts with the launch of SIRS-A which open an “exploration” phase during which different type of instruments are launched and scientists explore the potential of these data. This phase ended with the launch of HIRS-2 in 1978 when the data are considered operational by meteorologists.
B. This opens the second phase where it is demonstrated that these data have a negligible impact on the forecast in the north hemisphere[20]. This leads to the NASA/NOAA crisis and the freeze of the instruments. Meanwhile researchers on meteorology look for alternative assimilations methods, without any links to the satellite question. This phase ended in 1985 with the publication of the first paper on the potential and feasibility of variational data assimilation based on the pioneering (but still unpublished) work of le Dimet and Talagrand. It became clear that data assimilation was the reverse salient to integrate satellite data.
C. The 1986 paper unlock the research on this question. It almost immediately leads to the launch of the IFS/ARPEGE project at ECMWF and Meteo France under the leadership of Courtier and another at NOAA/NCEP lead by John Derber. The 1990 Clermont-Ferrand international symposium on data assimilation under the aegis of the WMO is a landmark in this story. It marks the convergence of the research on data assimilation and of the satellite data question. Moreover it signifies the recognition of the entire community and the beginning of the shift toward the variational scheme at the institutional level.
D. This phase ended with the implementation and the tipping of the NOAA/NCEP, ECMWF and, a bit latter, Meteo-France to the new variational regime that spread in the next decade.

Therefore what we see here is a new type of transition. We propose to call it *regeneration* since the regime transform itself in order to overcome the tensions but 1) without clear landscape pressure and 2) by combining continuity and change since it encompass existing elements and

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[20] Whereas in the south hemisphere, where observations were sparse, satellite date immediately had a positive impact. But 90% of the earth population is in the north hemisphere. Therefore this is the performance over the north hemisphere that is central to meteorologists.

radically new ones. Another case of this transition has been studied by Le Masson & al. (2012) in the case of semiconductors where the ITRS plays a central role in this continuous regeneration. This transition process is a mix between transformation[21] and reconfiguration since elements of the old regime remains in place while other experienced radical change (figure 5 below). It is close to transformation because regime actors survive but at the same time the implementation of 4D-VAR was not symbiotic and constitutes, conceptually, a radical departure from the preceding regime[22]. Analyzing the roots of this misfit with existing MLP typology is the topic of the next section.

Continuity	**Change**
✓ WMO ✓ Weather centers (ECMWF, Meteo France ✓ In-situ measurements systems ✓ Prediction models* / physics of the atmosphere ✓ Supercomputers* *continuously evolving	✓ Satellite data ✓ New data centers and organization to handle this new data (NOAA NESDIS, EUMETSAT) ✓ Coding / architecture of the model ✓ Variational data assimilation ✓ Conceptual foundation : optimal control (porté par de new acteurs).

Figure 5 : Elements of continuity and change in the transition process.

5.3. Studying agency in the MLP through projects

The misfit between the case and the transition probably comes from a change in perspective compared to existing MLP studies. Until now the dominant methodology of MLP studies is historical research over long time period. To take an example, Geels studies the transition from horse-based transportation to automobile over 70 years (1869 – 1930) or that from sailing to steam ships in the nineteenth century (1780 – 1900). This is coherent with the analysis of technological transition which are always long processes spanning decades. However this means that the researcher cannot go into the details of the transition process. This partly explains why some authors criticized the lack of agency in the MLP (Smith & al., 2005 ; Genus & Cole, 2008 ?). Actually it is almost impossible to study the strategy and practices of the actors

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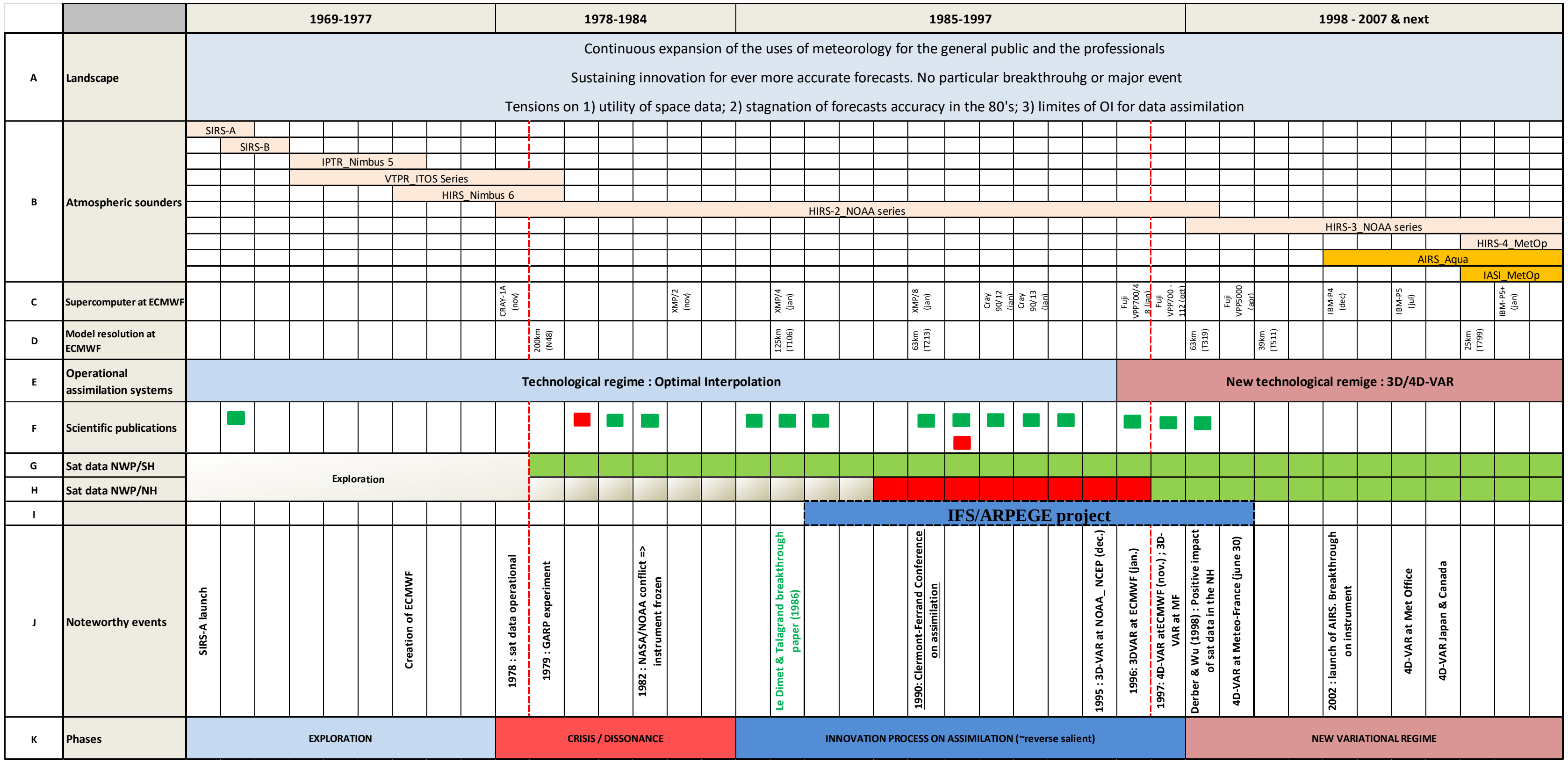
[21] In this path, new regimes grow out of old regimes through cumulative adjustments and reorientations (Fig. 5). Regime actors survive, although some changes may occur in social networks. Furthermore, regime actors may import external knowledge if the ‘distance’ with regime knowledge is not too large. Such symbiotic niche-innovations *add to* the regime and do not disrupt the basic architecture.

[22] This is visible in interviews with Courtier & Talagrand who explains that proponents of optimal interpolation never really understood the variational scheme because of their limited mathematical background.

involved in the transition over such a long time span and in 30 pages long research papers. And Geels answer to this critic is only half satisfying. His 2010 paper discuss the question of agency at the theoretical level of social science ontologies. He shows how the MLP, as a middle range theory, can make crossovers between the ontologies from its evolutionist/interpretivist foundations to rational choice, structuralism, functionalism, conflict/power and relativism. This is an important contribution that shows the strength of the MLP. However it remains theoretical and does not show agency in the making at the actors level. This is of course a considerable challenge since it is very difficult to simultaneously analyze the evolution of the different levels over the long run and the actor's role in these processes.

In this paper, and this is our third contribution, we suggest that focusing on the project-level could be a promising avenue for future research on technological transition. This approach is actually already present, although far from dominant, in the MLP, particularly in Rob Raven's work (2005) and Schot & Geels paper (2008). They show how succession of local projects may lead (or not) to regime transition (see also section 2). However they do not go to the actors level to analyze in detail the unfolding of the transition process. Our story show the case of a transition in which a project plays a central role in the transition from one regime to another. Indeed IFS/ARPEGE unlock the reverse salient (Hughes, 1983) of data assimilation. Even if this probably constitutes a particular case in technological transitions, the preceding story underlines the relevance of the project level to understand technological transition. Indeed in our case IFS/ARPEGE serve as a catalyst for the evolution of weather prediction. It brings together the elements needed for the transition: experts, money, computing power, institutional support, coordination mechanisms. IFS/ARPEGE creates the momentum and commitment necessary for the tipping of the community to the variational approach. Moreover the micro-analysis of the process at stakes helps to understand how the transition finally occurs. In this case we see a the continuity between the conceptual breakthrough from Le Dimet & Talagrand, the first demonstration of the feasibility of the method by Talagrand & Courtier and, finally, the implementation lead by Courtier who brings together the competencies needed : NWP, Mathematics of optimal control and computing. Therefore, at the project level, we can observe precisely the unfolding of the process and describe how the socio-organizational, technical, cognitive dimensions interacts (Raven & Geels, 2010).

Figure 6 : The transition from OI to 4D-VAR



This figure is based on the MLP. The upper part describes the landscape(A) and the evolution of the regime namely satellites (B), supercomputer (C) and numerical models (D), both following a sustaining trajectory of increased precision or power. Then come the assimilation methods (E), the reverse salient central that is in our study. Line F consist of the main scientific publications showing the problem with satellite data (red square) and the rise of variational methods (green). The impact of satellite data on NWP are shown in line G (south hemisphere) and H (north hemisphere). Line I represent the IFS/ARPEGE project. Line J summarizes the noteworthy events in our story. Finally line K display the phases of the process presented in section 5.2.

Beyond the specific case of NWP bridging the project and MLP literature constitutes in our view a promising avenue for research on technological transitions and for project management research. From the MLP perspective we have shown that project plays a central role in the innovation process. Given the cross-disciplinary nature of innovation (Van de Ven, 1986) project constitutes a dominant organizational form to manage the innovation process. Examples abound in which project leads to technological breakthrough and plays an important role in technological transition. Remember for example the atomic bomb project or in the late sixties the Arpanet project which both triggered major technological transition.We believe that MLP could benefit from a dialogue with project management research, particularly the management of highly innovative projects. Indeed there is an important renewal of project management research. Contemporary research makes it clear that managing highly innovative or exploration projects requires different managerial approach (Loch & al, 2006 ; Shenhar & Dvir, 2007 ; Lenfle, 2008 & 2011; Brady & Nightingale, 2011). And it is striking here to see the similarity between the lessons learned from the MLP and this body of work. For instance, in his study of biogas development in Denmark and the Netherlands, Raven (2005) underlines the strenght of the "parallel development patterns" in which different solutions are explored simultaneously. This, he argue, broaden the market share, accelerates learning and avoid the risk of being trapped with the wrong technology. This is exactly what the literature on project management shown for exploration projects (Klein & Meckling, 1958 ; Abernathy & Rosenbloom, 1969 ; Loch & al, 2006). So what we see appear here is a theory of agency in situation of exploration. Last, but not least, pioneering research by Von Pechman & al. (2015) on the electric vehicle analyze of firms can play (or more precisely try to play) a crucial role in technological transition by managing lineages of projects. Here again this echoes the findings by Raven on "continuous development patterns". Therefore we believe that contemporary PM research could provide a theory of collective agency in uncertain situations that is lacking in the MLP.

But the reverse is also true and project management research could also benefits from MLP findings. It is clear since the work of Engwall that "no project is an island" (Engwall, 2003). To understand the success of failure of a project Engwall brilliantly demonstrates that one has to take into account the "*contingencies influencing the interior process dynamics of a project*". And it points to past experiences, pre-project politics, institutional norms routines and value of the context and parallel course of events evolving in the context as examples of these contingencies. This is an important contribution but it is not grounded in a theory of the dynamics of the context. And this is a central question for all projects in charge of designing radical innovations. This is where bridging MLP and Project Management research could be fruitful. Indeed the MLP provides a theory of technological transitions that could also constitute a guide for action.

6. Conclusion

We started this paper by discussing the current limitations of the multi-level perspective, currently the leading theoretical framework to discuss technological transitions. In particular we point, following Smith & al (2005), Genus & Cole (2008) and Geels (2011) to the question of agency which is downplayed in the MLP. We suggest than one avenue to deal with this question could be to bridge, as suggested by Geels, the MLP with "*insights from business studies and strategic management*" (p. 30). This lead us to present and analyze the case of a transition in a large technical system, namely the "quiet" revolution of numerical weather prediction triggered by the introduction of revolutionary observation systems : weather satellites. The key moment in the process was the launch of a major project to develop and implement a new assimilation technique. It overcomes the reverse salient of data assimilation. We thus suggest that this represent a new type of transition name regeneration in which the regime transform itself without landscape pressure by combining existing elements and radically new ones. This shed new light on the MLP since we uncover elements of continuity and change. We also demonstrate that the project level could be a fruitful level to study agency in the MLP. It constitutes an intermediate level between the individual actors and the regime and constitutes historically an important organizational vector to develop innovations. Finally we suggest that cross-fertilization between project management and MLP research constitutes an important avenue for future research. No doubt that further research is needed in this direction.

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8. <u>Appendix: Sources and references on meteorology and Numerical Weather Prediction</u>

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8.3. Interviews

Name	Institution	Location and date
Olivier Talagrand	CNRS – LMD	LMD, Paris, le 26 mai 2014
Jean Pailleux	Météo France et ECMWF	Paris, le 4 juin 2014
Philippe Courtier	Météo France et ECMWF	Champs sur Marne, le 13 juin 2014
Philippe Courtier	Météo France et ECMWF	La Défense, le 15 juillet 2014
John Derber	NOAA/NCEP	By email on 28/7/2014 & 1/9/2014 then at the ECMWF on 8 septembre 2014.
Olivier Talagrand	CNRS – LMD	LMD, Paris, le 5 septembre 2014
Jean-Noël Thépaut	Météo France et ECMWF	ECMWF, le 8 septembre 2014
Florence Rabier	Météo France et ECMWF	ECMWF, le 8 septembre 2014
François-Xavier Le Dimet	Université de Grenoble et INRIA/MOISE	Grenoble, le 11 septembre 2014
Philippe Veyre	Météo France et CNES	CNES, Paris, le 4 février 2015