Submarine cables deployment, digital vulnerabilities and the digital divide in Sub-Saharan Africa*

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Abstract

While the massive laying of fiber optic submarine cables (SMCs) over the subcontinent in the last decades raised the prospects for the digital economy's expansion in sub-Saharan Africa (SSA), this deployment may have made the telecommunication sector subject to new vulnerabilities. On the one hand, SMCs are vital nodes of the telecommunication network, and their recent laying in SSA, though having boosted the digital economy, has also increased the sub-continent vulnerability to SMC outages. On the other hand, the laying of SMCs has widened the spatial digital divide within the sub-continent and within countries: between coastal or urban populations close to SMC landing stations and key other backbone infrastructures, and isolated inland or rural populations with low infrastructure coverage and more exposed to telecommunication network failures. This paper studies the impact of SMC deployment on the SSA's digital divide, and highlights the importance of aforementioned digital vulnerabilities: the country's exposure to SMC outages and digital isolation. Diff-in-Diff estimations of the impact of different waves of SMC arrival on internet penetration rates are conducted, and stress a 1%-significant four percentage-point increase in Internet penetration rates following the laying of these cables. However, the panel data analysis points that digital vulnerabilities related to SMC deployment negatively affect Internet and mobile penetration rates, ICT investments, and positively affect prepaid mobile cellular tariffs and the wireline network instability.

Keywords: ICT, submarine cables, infrastructures, telecommunications, Sub-Saharan Africa

JEL codes: F02, L96, O33, O18

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1. Introduction

Information and Communication Technologies (ICTs), more particularly broadband internet and mobile technologies are general-purpose technologies playing an increasing role in the development process. By contributing to the emergence and dissemination of innovations in trade, agriculture, financial services or transportation, and to the modernization of public administrations, including tax administration, the digitization of the economy raised the prospects of growth, employment and poverty reduction in Sub-saharan Africa (Aker & Mbiti, 2010; Andrianaivo & Kpodar, 2011; World Bank, 2016; Hjort & Poulsen, 2017). However, in the sub-continent, the expected dividends of digital technologies are slow to materialize and to benefit the whole population (World Bank, 2016). These low 'digital dividends' are seen as the result of the telecom infrastructure deficit (Schuman & Kende, 2013; Buys et al, 2009, Bates, 2014) and the poor governance of the telecommunication sector (Howar & Mazaheri, 2009; Akue-Kpakpo, 2013; Sutherland, 2014). Therefore, and despite the high penetration rate of mobile telephony in the continent, access to broadband in sub-Saharan Africa (SSA) primarily benefits to the rich, the urban, and the most educated (World Bank, 2016).

During the last decade, global connectivity has improved significantly with the worldwide deployment of more than 320 fiber submarine cables (SMC) over the period 1990-2017, transmitting 99% of International telecommunications, the remaining 1% being transferred by satellite. Among developing areas, Asia, South America and North Africa were quickly plugged to the North through SMCs; while SSA remained relatively isolated until 2009. Since then, the digital infrastructure quickly unfolded, facilitating access and reducing the cost of broadband internet and mobile telephony. Today, almost all coastal African countries are directly connected to the global internet through SMCs. If the internet penetration is still low in SSA compared to other developing regions, the strong dynamism of the mobile industry is an important lever for the development of the digital economy (ITU, 2016).

In Africa, the growth prospects from the digital economy expansion are particularly important. According to the United Nations, Africa should shift from 1 billion inhabitants in 2014 to 2.4 billion in 2050, representing one quarter of the world's population, with a 15-24 year-old population rising from 200 million to more than 700 million in 2050 (30% of the population African). It is therefore on this continent that economic and social changes related to digital technologies dissemination may be the deepest. The digital dividends for growth, employment and diversification in sub-Saharan African economies could however be significantly improved by an environment more conducive to the development of the telecommunications infrastructures (Ndulu, 2006; Schumann & Kende, 2013).

This paper brings new insights into the digital divide determinants in SSA, by analyzing how the maritime infrastructure deployment has affected the telecommunication sector development in the subcontinent. First, this paper contributes to the literature by providing novel evidence on the impact of different waves of SMC arrivals on ICTs outcomes. Second, it highlights how the deployment of SMCs is associated with new sources of vulnerability for the telecommunication sector.

Digital vulnerability is defined as the risk for a country and its population to get the access to telecommunication services hindered by failures in its telecommunications networks. SMCs are vital nodes of the telecommunication network, and their recent laying in SSA, though having boosted the digital economy expansion, has also increased the sub-continent vulnerability to SMC outages. This vulnerability is particularly strong in low-resilience countries relying on few SMCs to reroute telecommunication traffic. As a recent illustration, on March 30 2018, damage to the Africa-Coast-to-Europe (ACE) cable disrupted telecommunications in some 10 African countries, but more severely in six countries hosting only one cable (the ACE cable), which were unable to reroute and stabilize the telecommunication traffic.[2] In June 2017, the anchor of a container ship cut accidentally the unique SMC linking Somalia to the world Internet, depriving the country of the Internet for more than three weeks and causing 10 million USD economic losses a day.

Moreover, the laying of SMCs has also increased the spatial digital divide within the sub-continent and within countries[3]: between coastal or urban populations (the core) close to SMC landing stations and key other backbone infrastructures, benefitting from a faster and more stable telecommunication network, and isolated inland or rural populations (the periphery) with low infrastructure coverage and more exposed to telecommunication network failures. In a core-periphery infrastructural setting, populations remote from vital infrastructure nodes face failing telecommunication services. This pattern is explained by the lacking terrestrial infrastructure coverage and maintenance in many African states, and by the spatial hierarchy in telecommunications nodes favoring urban and coastal areas when disruptions occur (Malecki, 2002; Grubesic, O'Kelly, and Murray, 2003; Gorman et al, 2004; Grubesic and Murray, 2006). As a result, some countries with populations sparsely distributed over large or landlocked territories might exhibit a larger spatial digital divide after the laying of SMCs.

The contribution of SMC arrival and related digital vulnerabilities – that is, the SMC exposure to shocks and the digital isolation – to the telecommunication sector development are estimated. Estimations are conducted using telecommunication development variables aimed to reflect five outcomes of the telecommunication sector: the Internet penetration, the mobile penetration rates as final outcomes variables; and the telecommunications tariffs, the telecommunication investments, and the telecommunication network stability as intermediary outcome variables. The empirical approach is then developed in two steps. First, the impact of SMC deployment on Internet and mobile penetration rates is studied using a Difference-in-Difference (DID) estimation framework, looking at the evolution of penetration rates before and after different waves of SMC arrival on the sub-continent. Second, sources of digital vulnerability and their effect on both final and intermediary outcomes are brought to light, through a panel data analysis conducted on a sample of 46 African countries over 1995-2014.

DID results stress that the deployment of the SEACOM/TEAMS and Main1/Glo1/EASSy cables in 2009 and 2010 is associated with a 3-4 percentage point increase in Internet penetration rates in SSA. Then, the panel data analysis points to the negative impact of digital vulnerability on the telecommunication sector development. In general, including digital vulnerability variables in regressions strongly increases their explanatory power, especially digital isolation proxies. In particular, results stress i) the negative effect of digital isolation and SMC exposure to shocks variables on Internet penetration rates, mobile penetration rates, and telecommunication investments; and ii) their positive effect on prepaid mobile-cellular connection tariff and on the telecom network instability. Therefore, while the arrival of SMC in Africa has boosted the digital economy, the digital divide would be lower if SSA countries were less exposed to SMC outages and if populations were less geographically isolated.

Therefore, this paper provides new insights into the literature on the determinants of the digital divide in developing countries (Wallsten, 2005; Howard & Mazaheri, 2009), especially SSA (Ndulu, 2006; Buys et al, 2009). First, this paper exploits a novel database on various features of the SSA's telecommunication infrastructure network to analyze ICTs' development in the sub-continent. Second,

[2] These six countries – Sierra Leone, Mauritania, Liberia, Guinea-Bissau, Guinea, Gambia – displayed lower redundancy that the four remaining countries – Benin, Senegal, Ivory Coast, Equatorial Guinea. See Meyer, D. "An Entire Country's Internet Was Cut Off for 2 Days After an Underwater Cable Broke", Fortune, April 9, 2018, and also Belson, D. "ACE Submarine Cable Cut Impacts Ten Countries", Oracle Internet Intelligence, April 5, 2018.

[3] Despite reducing the international digital isolation of many African states.

this paper quantifies the macro-level impact of SMC-laying on various telecommunication outcomes through a Diff-in-Diff econometric analysis. Except for Hjort and Poulsen (2017), who conducted a DID micro-level analysis to study the impact of SMC deployment on job creation, such an approach has not yet been applied at the macro-level in SSA to a wide range of ICT variables. Third and most importantly, this paper highlights both the benefits and the risks brought by SMC deployment, by providing evidence on the potential vulnerabilities inherent to their arrival in SSA.

The next section exposes a descriptive and comparative analysis of the contribution of the telecommunication infrastructures deployment and emphasizes structural digital vulnerabilities that may arise therefrom. A DID approach is implemented in the third section to identify the impact of SMC deployment on the digital divide in SSA. Then, in a fourth section, a panel data analysis highlights how digital vulnerabilities related to SMC deployment affect telecommunication outcomes in the sub-region. The fifth section concludes.

2. Maritime infrastructure deployment and digital vulnerability in sub-Saharan Africa

This section offers an overview of the interplay between the sub-Saharan African ICT sector performance and the expansion of international telecommunications infrastructures in the sub-continent. It also introduces the notion of digital vulnerability related to failures in the telecommunications infrastructure network. In fact, by plugging coastal African countries to the global digital economy, high-capacity telecommunication infrastructures make populations that are remote from them more digitally isolated, and countries more vulnerable to their eventual collapse.

2.1. Appraisal of the maritime telecommunication infrastructure deployment in sub-Saharan Africa

In 2018, Sub-Saharan Africa (SSA) is connected to the world Internet through 15 SMCs, nine being spread over its West coast, and 6 over its East coast.[4] The laying of these cables has accelerated the development of the digital economy through a greater access to affordable and fast Internet and mobile technologies, thereby improving the performance of firms (Cariolle et al, 2017, Paunov & Rollo, 2015, 2016), facilitating job creation (Hjort & Poulsen, 2017), increasing trade flows and foreign direct investments (Freund & Weinhold, 2004), and enhancing governance quality (Andersen et al, 2011, Asongu & Nwachukwu, 2016). The potential benefits of the deployment of SMCs are therefore very important (Röller & Waverman, 2001; Czernich et al, 2011). The following subsections review the literature on the contribution of maritime infrastructure to the telecommunication sector, and provide some stylized facts on the relationship between this infrastructure's expansion and access to ICTs in SSA.

Descriptive evidence on the deployment of SMCs and its consequences for the telecommunication sector in sub-Saharan Africa

The global network of submarine fiber-optic wires represents the first link in the Internet access chain, and the most efficient option to deliver international telecommunications services (e-mail, phone calls, content videos, etc.). In the absence of submarine telecommunication cable (SMC), a country has two solutions to get an international Internet connection: i) buying expensive and limited Internet

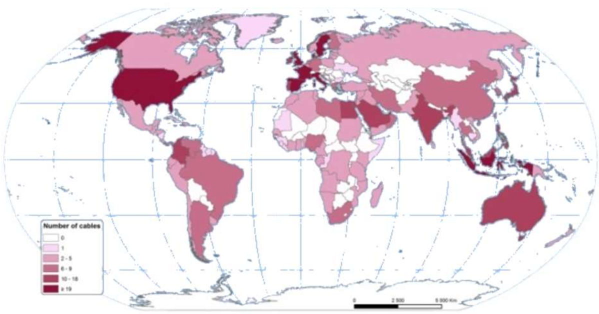
[4] **West-coast cables**: SAT3/SAFE (800 gigabits capacity), GLO-1 (2.5 terabits), ACE (5 Terabits), MainOne (10 terabits), NCSCS (12.8 terabits), WACS (14.5 terabits); SAIL (32 terabits), SACS (40 terabits), EllaLink (72 terabits) are expected in 2018. **East-coast cables**: SEAS (320 gigabits), TEAMs (1.2 terabits), LION 2 (1.3 terabits), EASSy (10 terabits), Seacom (12 terabits); DARE (60 terabits) is expected in 2018.

bandwidth to a neighboring country, connected through SMC (which supposes to be connected to that country by a terrestrial wireline infrastructure), or ii) buying Internet bandwidth - costly, slow and limited - to communication satellites.

SMC deployment is therefore the first step towards global Internet access, and is a subsequent catalyst for terrestrial infrastructure investments, by making them more profitable (Schumann and Kende, 2013). The increase in the number of SMCs connecting countries to the global Internet enlarges the total bandwidth available to Internet users, reduces the cost of Internet services, intensifies competition in the telecom sector, improves Internet redundancy, and reduces the impact of cable outages (Weller and Woodcock, 2013, Schumann and Kende, 2013, Telegeography, 2016).

Figure 1 maps the number of SMCs by countries in 2015 and shows that Sub-Saharan Africa, in regard to its international digital connectivity, is lagging compared to Asia and Latin America. International connectivity of the whole continent is indeed relatively low, and the continent displays a large number of landlocked countries without access to the sea for which the deployment of the terrestrial infrastructure is more complex (i.e. required to cross several borders) and more expensive. This delay in SMC deployment explains both the lesser geographic coverage of national and regional Internet networks, and the high cost passed on Internet services which can sometimes reach 30 to 40 times that of the inhabitants of developed countries (Towela and Tesfaye, 2015).

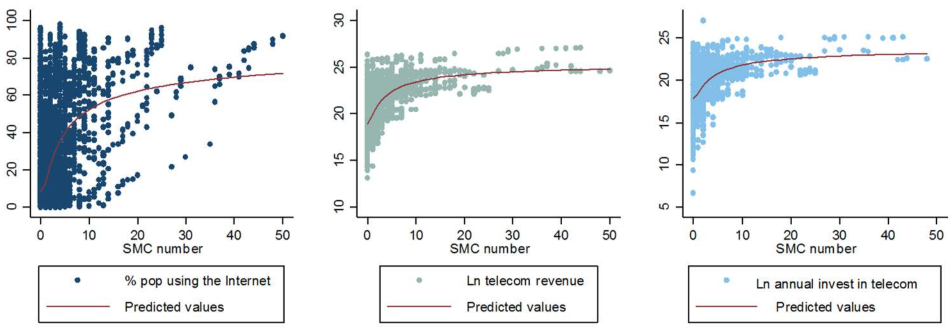
Figure 1. Number of fibre SMCs in 2015.



Source : Telegeography

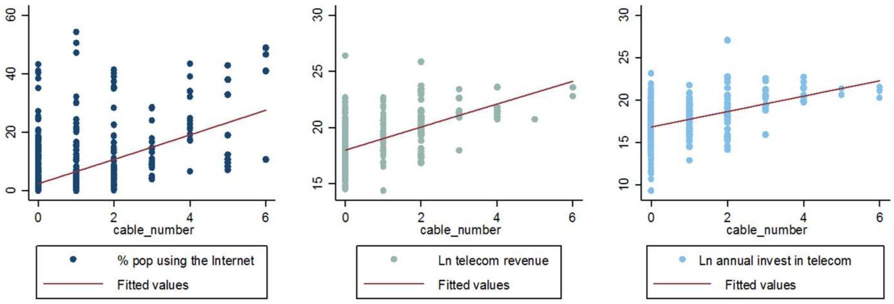
Last, to illustrate the interplay between the deployment SMCs and some telecommunication outcomes, the worldwide graphical correlation between the number of SMCs and three common metrics of the Internet economy's dynamism is illustrated in figure 2. Figure 3 reports the same correlation applied to sub-Saharan African countries only. These graphics put in evidence a positive correlation of SMC deployment with Internet penetration rates, and with the revenues and investments of the telecom sector.

Figure 2. SMC deployment and the telecom sector, world evidence, 1990-2014.



Source : Raw data from ITU (2016) and Telegeography (2016).

Figure 3. SMC deployment and the telecom sector, Sub-Saharan Africa, 1990-2014.



Source : Raw data from ITU (2016) and Telegeography (2016).

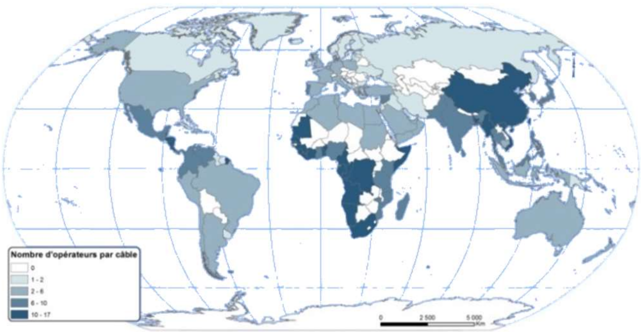
SMCs, fixed costs, and the maturity of the telecommunications market

SMCs require very large investments, reaching hundreds of millions of dollars (Weller & Woodcock, 2013). This high fixed-cost is a strong barrier to entry that may maintain some populations, countries and regions digitally isolated from the rest of the world. Once these investments are made, they allow telecommunications operators to acquire a significant market power, which is normally brought to decrease over time when fixed costs are amortized and economies of scale are exploited.

First, in less mature markets, a solution to overcome the high cost of SMC deployment consists in the building of large transnational consortia grouping together public and private operators and investors. Such Consortia allow the sharing of fixed costs, the leverage for additional funding, and thus the facilitation of SMC-laying. Such enlarged multi-stakeholders financial and ownership scheme has been adopted for the deployment of the ACE cable in West Africa (Perret et al., 2013), and for the deployment of the EASSy cable system in East Africa (Sihra, 2013). Figure 4 below stresses that the average number of operator owners by SMC in the western and southern parts of the African continent is particularly important compared to the rest of the world.

Moreover, these consortia foreshadow interconnection and interoperability agreements between local, national, and regional internet networks, which may in turn affect the competitive environment in the countries concerned by the arrival of cables. Figure 5 shows that cost-sharing – measured by the total number of operator owners of SCM by country – is positively correlated with the development of the digital economy in SSA. However, without effective regulation of the market ensuring an open and competitive environment, these consortia can lead to cartel agreements between operators and/or internet service providers (ISPs). In such a configuration, operators/ISPs may benefit from excessive market power that hinders ultimately the development of infrastructure and the growth of the telecom sector.

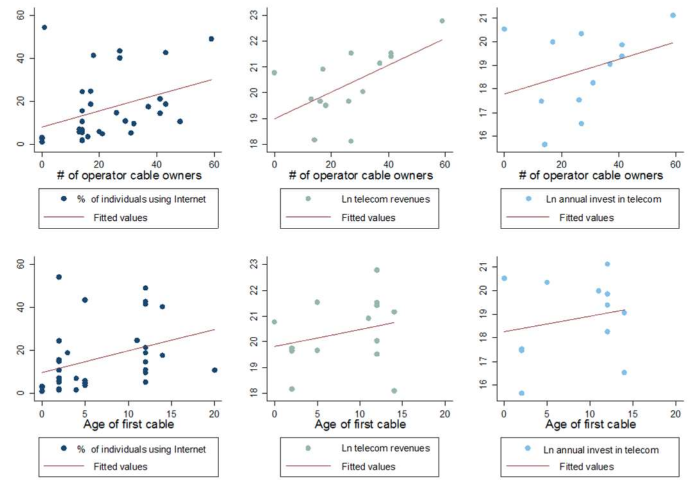
Figure 4. Average number of operators by SMC, in 2015.



Source : Telegeography (2016).

Second, given the importance of the cost of SMC deployment, the number of years passed since the first SMC arrived in a country also provides useful information on the degree of maturity of the telecommunications market in this country: the more mature the market, the earlier SMC arrival, the better the exploitation of scale economies. The first SMC's seniority should therefore be positively correlated with the development of the digital economy, which is confirmed by the bottom correlation graphs represented in figure 5. These two characteristics of the maritime infrastructure network – i.e. the number of operators sharing the costs of SMCs on the one hand, and the seniority of the first SMC on the other hand – therefore appear as relevant proxies of the telecommunication market development.

Figure 5. Infrastructures and the telecom market development in SSA



Source: Author based on ITU data (2016) and Telegeography (2016).

2.2. SMC deployment and digital vulnerability in Sub-Saharan Africa

Digital vulnerability is defined as the risk for a country and its population to get the access to telecommunication services hindered by failures in its telecommunications network. These failures may result from the under-capacity or gradual obsolescence of the telecommunications infrastructure network, as well as its exposure to recurring external shocks and internal failures (breakdowns of server, SMC-outs, closing data-centers of Internet exchange points), power outages, and cyber-attacks. In this context, digital resilience would be the ability of the telecommunications network to ensure the permanence of the capacity and the stability of telecommunication services.

In this paper, the analysis focuses primarily on digital vulnerabilities accompanying the deployment of SMCs.[5] Once a country is plugged to the rest of the world through SMC, countries are exposed to two structural interrelated sources of digital vulnerability, independent from policy: i) their exposure to SMC outages, and ii) the digital isolation resulting from the geographical distance to SMC landing stations, and making isolated countries and remote populations even more exposed to telecommunication failures (Grubesic and Murray, 2006; Grubesic et al. 2003).

[5] And therefore does not address the question of Internet exposure to power outages and cyber-attacks, to which the analysis would be equally applicable and informative (Grubesic and Murray, 2006).

The exposure to SMC outages

The recent and massive laying of fiber SMCs in SSA is considered as a major driver of progress for mobile and Internet penetration, and for the digital economy's expansion as a whole. However, SMC deployment over the sub-continent has also increased its vulnerability to SMC outages. The increasing occurrence of cable cuts, induced by maritime activities or natural hazards, and their damaging effects on African economies represent a major concern for digital eco-systems. This concern is even stronger in a number of low-resilient African countries, which rely on few SMCs to get access to international communications.

Between 2008 and 2012, with data collected by Palmer-Felgate et al (2013) indicate that 471 repairs of damaged cables have been undertaken worldwide, geographically distributed as follows: 186 repairs in the Atlantic ocean, 115 in the Mediterranean Sea, 93 in the Asian Pacific Ocean, 68 in the Indian Ocean, and 9 in the region of North-American Pacific Ocean. These outages broadly result from two principal sources (Carter et al, 2009; Clark, 2016):

- Human activities: mainly maritime activities (fishing nets, anchors), which are the most common cause of outage, but also acts of piracy and sabotage.
- Natural events: such as seism, typhoons, floods, volcanic eruption, turbidity currents, which provoke about 30% of deep-water SMC outages[6], and are the main cause of multiple simultaneous SMC breaks.

In addition to firms' direct costs of repairing damaged cables for telecoms operators, amounting to millions of dollars depending on cable repair frequency and length, there are indirect economic costs, rising to tens or hundreds of millions of dollars related to (Widmer et al., 2010; Clark, 2016, Aceto et al., 2018):

- The reporting of repair costs and insurance costs on communication tariffs and its consequences for Internet and mobile penetration;
- The rerouting of the traffic towards more expensive cable paths and its consequences on communication speed, volume and tariffs;
- The disorganization of global manufacturing chains and Internet-related service provision (e.g., financial services).

Moreover, these direct and indirect costs are amplified by delays in cable repairs. According to Palmer-Felgate et al. (2013), these delays vary significantly among maintenance areas and countries, and mostly result from multiple outages induced by natural events such as earthquakes or typhoons, ships engaged in prior repairs (likely induced by multiple outages), repair permit acquisition delay, or operational issues (Borland, 2008).

First, SSA is exposed to cables outages that are mainly caused by maritime traffic (fishing nets, anchors from boats). The 10th of July 2009, the SAT-3 cable breakdown linking Europe to West and South Africa disrupted telecommunications in Benin, Togo, Niger, and Nigeria. In May 2011, a new SAT-3 cable break caused by a boat anchor deprives Internet users in Benin, Togo, Niger, Burkina Faso and Nigeria for 10 to 15 days. More recently, in June 2017, the Main-1 cable breaks 3000 km to the South of the Portugal disturbing the Internet in several countries in West Africa. The same month, the anchor of a container ship cut accidentally the unique SMC linking Somalia to the world Internet, depriving the country of the Internet for more than three weeks and causing economic losses estimated by the Government of Somalia to more than 10 million dollars a day. Table 1 below reports SSA

[6] According to 2006 statistics (Carter et al, 2009), but probably much more today given the dramatic densification of the worldwide SMC network.

countries affected by cable breaks from 2008 to 2017, based on the study of the information available on the web (see details in Appendix B.4).

Table 1. Occurrence of Sub-Saharan African cable breaks, reported on the web.

Country/region	year	# breaks	Country/region	year	# breaks
West-Africa	2017	1	Niger	2011	1
East-Africa	2016	1		2009	1
	2010	1	Nigeria	2015	1
South Africa	2016	1		2012	1
Benin	2011	1		2011	1
	2009	1		2009	1
Burkina Faso	2011	1	Rwanda	2012	1
Burundi	2012	1	Somalia	2017	1
Cameroun	2017	1	Tanzania	2012	1
Congo Rep.	2017	1		2010	1
Djibouti	2008	1	Togo	2011	1
Gabon	2015	2		2009	1
Kenya	2012	1	Zambia	2008	1
	2010	1		**TOTAL**	**23**

Source : author. Most data is gathered from https://subtelforum.com/category/cable-faults-maintenance/ , cross-checked and complemented with keyword-based internet searches.

Second, SSA's maritime infrastructure is also exposed to seismic risk.[7] In fact, Seismic activity is a major cause of direct or indirect cable breaks by provoking turbidity currents, landslides, and tsunamis (Soh et al., 2004; Carter et al., 2009; Clark, 2016, Aceto et al., 2018). Compared to other sources of SMC outages, seaquake-induced cable breaks may lengthen the time needed to repair cables by inducing simultaneous multiple outages (Palmer-Felgate et al., 2013), and may therefore be costlier for the economy. I document this exposure in SSA in table 2, exploiting information on the location, timing, frequency, and intensity of seaquakes, to build a variable of a *country's exposure to seaquake-induced cable outages*: the annual frequency of seaquakes that occurred within a radius of 500km from SSA's SMC landing stations between 1995 and 2014.[8] The data stresses that East-Africa and in a lesser extent Central Africa's infrastructure are two sub-regions exposed to the risk of seaquake-induced cable outages.

[7] Though in a much lesser extent than Asian or Caribbean countries (See Cariolle et al., 2017).

[8] The focus placed on seaquakes is explained by the fact that earthquakes cause damage to the whole economy and therefore not only to telecommunication networks. To better identify the impact of this exposure variable, we only considered seaquakes above 5 on the Richter scale. This lower bound has been chosen according to Soh et al. (2004), who find that in the eastern part of Taiwan cable breaks occurred following earthquakes ranging from 5.0 to 6.0 on the Richter scale.

Table 2. Annual seaquake frequency above 5 on the Richter scale in SSA, 1995-2014.

Country	year	Seaquake freq.	Country	year	Seaquake freq.
Angola	2001	1	Kenya	2005	1
RDC	2001	1	Madagascar	2013	1
Congo, Rep	2001	1	Sudan	1996	1
Comores	1995	2		2001	1
	2000	1		2009	1
	2002	1		2010	1
	2005	2		2013	2
	2007	3	Somalia	1997	3
	2008	3		1998	2
	2010	1		2000	3
	2012	2		2001	6
Cap Verde	1998	1		2002	3
Djibouti	1997	2		2003	2
	1998	2		2004	2
	2000	2		2005	2
	2001	1		2006	6
	2002	1		2007	2
	2003	1		2008	3
	2004	1		2009	6
	2005	1		2010	27
	2006	1		2011	4
	2007	2		2012	2
	2008	2		2013	2
	2009	4	Seychelles	1995	1
	2010	25		2003	1
	2011	3	Tanzania	2005	3
	2012	1		2008	3
	2013	2		2010	1

Source: author. Data retrieved from Telegeography and the Northern California Earthquake Data Center.

Therefore, SSA is exposed, as many other developed and developing areas, to SMC breaks that could induce substantial social and economic losses. This exposure is particularly problematic for SSA countries, given the relative low number of SMCs connecting countries in the subcontinent (see Figure 1), which display low resilience to SMC outages. In the following sub-section, the geography of SSA – consisting of many large, landlocked and rural countries – is identified as an additional factor of digital vulnerability.

Distance to SMC, digital isolation and the digital divide

In 2016, most coastal developing countries are connected to the global economy by SMC. However, the arrival of SMCs in Africa has only reached a limited share of the African population – mostly rich, educated urban and coastal people – so that the digital divide plays now more at the subcontinent or country-levels rather than the global-level. As a result, inland infrastructure deployment is considered as one of the major challenges for the telecom industry and the whole economy in low-income countries, especially SSA countries (Ndulu, 2006; Nyirenda and Tesfaye, 2015, Bates, 2014; Weller and Woodcock, 2013). And even though the terrestrial infrastructure span could reach a major part of the population, a general rule stating that the cost of (internet) communication is equal to its speed multiplied by the distance traveled (Weller and Woodcock, 2013), makes the average distance between the user and key telecommunications infrastructure nodes a critical determinant of the digital divide.

In addition, some studies have stressed how locations that are geographically isolated or underserved by the telecommunication infrastructure are more vulnerable to infrastructures outages, including large telecommunication disruptions induced by SMC outages. Grubesic and Murray (2006) show that in countries where telecommunication assets are concentrated in few places, telecommunication networks cascading failures following infrastructure collapses are more likely to occur. They also point that locations that are remote from telecommunication vital nodes are particularly exposed to telecommunication disruptions. Moreover, Grubesic et al. (2003) show that digitally-isolated locations are slower to recover after network disruptions, and therefore incur larger economic and social costs from the experience of telecommunication shutdown. As result, the geography of many SSA countries – characterized by large territories, landlockedness, an important rural population, and infrastructures concentrated in capital cities and coastal areas – increases the likelihood and the negative impact (in terms of geographical coverage and persistence) of telecommunication disruptions following infrastructure outages.

Digital isolation in some areas therefore depends on both structural geographical factors, such as the geographical fragmentation of the continent, landlockedness, the size of the country, the altitude, the spatial distribution of the population; and policy-related factors, such as the quality of regulation and the extent of public and private investment in the telecom sector. The study of the geographic determinants of digital isolation, by their structural and exogenous nature, is of particular interest here.

To study the geographical determinant a country's digital isolation, three distance variables have been computed:

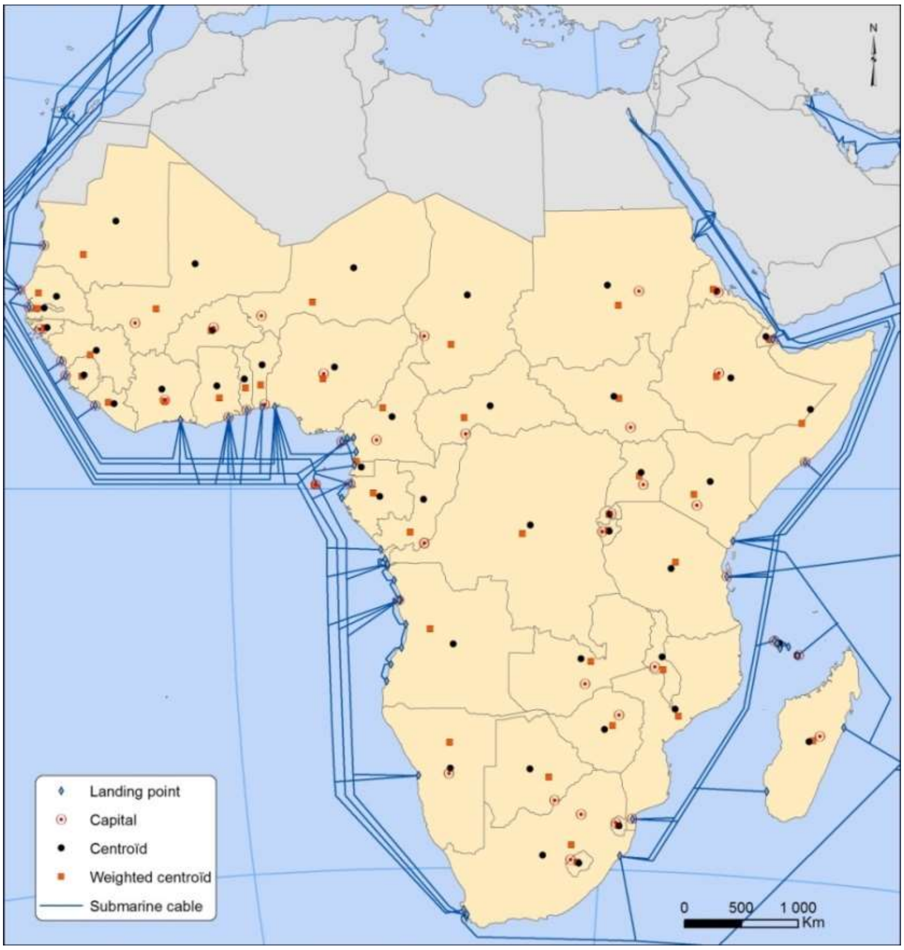
- The **geographic centroid distance**, i.e. the distance between the geographic centroid and the closest SMC landing station.[9] This geographic distance is the bird's eye distance required for the deployment of the backbone telecom infrastructure that minimizes the infrastructure gap for any random locations in the territory.
- The **capital distance**, i.e. the distance between economic capitals and the closest SMC landing station. This capital distance is the bird's eye distance required for the deployment of the backbone telecom infrastructure to reach the principal demographic and economic center.
- The **demographic centroid distance**, i.e. the distance between the geographic centroid weighted by the spatial distribution of the population (denoted as the demographic or weighted centroid) and the closest SMC landing station. This demographic distance is the bird's eye distance required for the deployment of the telecom infrastructure that minimizes the average infrastructure gap with the whole population. This distance is a mix of the geographic distance and the capital distance previously mentioned.

The geographical distance to SMC reflects the geographical handicaps faced by large and/or landlocked countries to bring ICTs over the whole territory. The capital and demographic distance both reflect the geographical handicap faced by large, landlocked, and rural countries to bring ICTs to their population. The longer these distance, the more likely the digital isolation of the population. The

[9] When one country does not host a SMC, the distance to the closest SMC landing station among neighbor countries is calculated.

map in Figure 6 below gives an idea of these distances in SSA, by plotting the countries' centroid, weighted centroid and capital against SMC landing stations.

Figure 6. Capitals, geographic and demographic (weighted) centroids, and SMC landing stations in Sub-Saharan Africa in 2017.



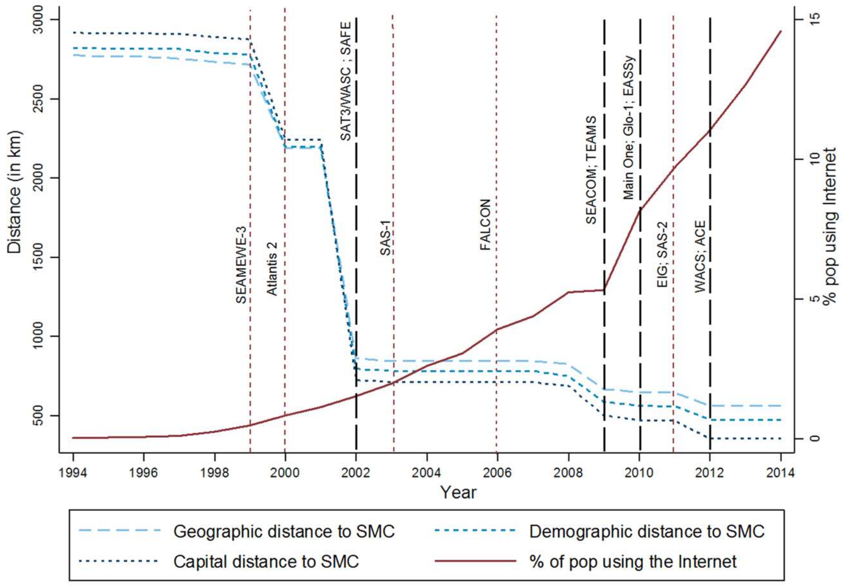
Sources : Author. See Appendix B for details on centroids calculation.

Figure 7 below represents the different waves of transcontinental SMC deployment together with the evolution of the geographic, capital and demographic distance to the closest SMC landing stations, and the evolution of the average Internet penetration rate in SSA. Regional SMC waves (plugging more than two countries to the global Internet) are identifiable by long-dashed lines while local SMCs (one or two connected countries) are identifiable by short-dashed lines. This graph stresses that the waves of transcontinental SMC arrival track the decreasing trend in needs for infrastructures, and the increasing trend in the sub-regional Internet penetration rate. Notably, the SEACOM and TEAMS cables arrival – connecting South Africa, East Africa, and Djibouti, and Egypt to India and the United Arab Emirates – are associated with a striking regime shift in the average Internet penetration rate's evolution.[10]

Figure 8 stresses that the dispersion of the distances to SMCs faced by African countries underwent a sharp decline around 2009, corresponding to the plugging of most coastal African countries to the 'global village' by SMC. Therefore, starting 2009, digital isolation in Africa mainly relies on policy-makers and operators' ability to reach isolated countries and locations.

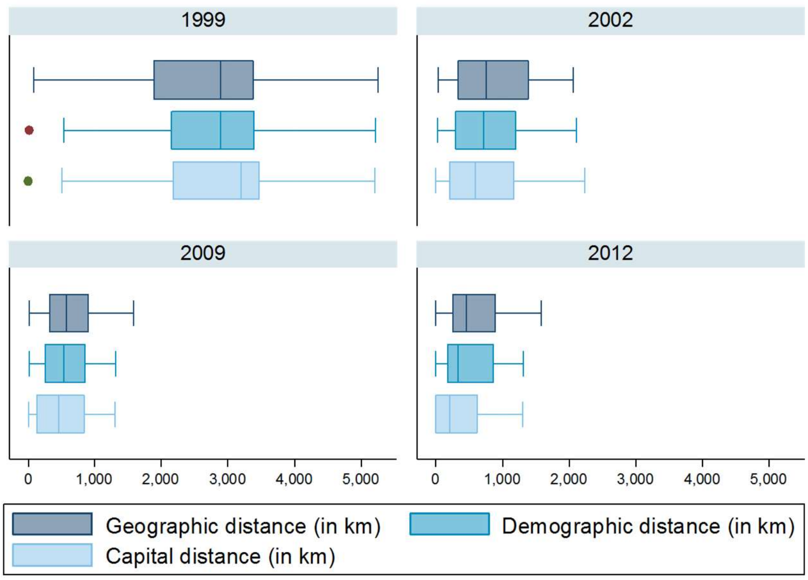
[10] This feature will be exploited in the next empirical sections.

Figure 7. Declining average distances to SMC landing stations and waves of transcontinental SMC deployment in SSA.



Source: author. Long-dashed vertical lines: arrival of a transcontinental regional SMC (plugging more than 2 countries). Short-dashed vertical lines: arrival of a transcontinental local SMC, plugging one or two African countries.

Figure 8. Distributions of distances to SMC landing stations of Sub-Saharan African countries, following major regional SMC deployment.



Source: author.

In summary, the rapid and worldwide deployment of SMCs had a significant impact on the development of the telecommunications sector in SSA, boosting the 'digital revolution' in subcontinent. Coastal countries in SSA are now almost all connected to the global Internet by SMC, the digitization of the subcontinent is facing two main structural factors of digital vulnerability. On the one hand, African countries are exposed to the risk of SMC outages, with a dramatic impact on the telecommunications sector development and the economy as a whole. On the other hand, many large, landlocked or rural African countries, which populations are distant from SMC, may suffer from greater digital isolation and be deprived from an affordable and stable access to ICTs.

3. Empirical analysis

This empirical analysis tries to unravel the contribution of the submarine telecom infrastructure to telecommunication sector outcomes, by studying the impact of the deployment of SMCs on the one hand, and the impact of new digital vulnerabilities related to their deployment on the other hand.

3.1. Empirical settings

The empirical analysis exploits a panel dataset covering about 46 African countries over the period 1990-2015. In a first step, I adopt a difference-in-differences (DID) approach (David and Krueger, 1994; Heckman et al. 1998) to study the impact of different waves of SMC arrivals on final telecommunication outcome variables. Among the different waves of SMCs that plugged SSA to the global Internet, only regional SMCs, i.e. SMCs that plugged at least three sub-Saharan African countries together or to another continent, were considered. In fact, SMCs connecting one our two countries to the global Internet could make SMC arrival related to national policy-related factors rather than aggregate regional considerations, and therefore make the treatment endogenous. Among the various waves of SMC arrivals (see figure 8) in SSA, the following are studied:

1. the SAT3/WASC/SAFE wave in 2002, plugging South Africa, Angola, Gabon, Cameroun, Nigeria, Benin, Ghana, Ivory Coast, Senegal, and Mauritius to Asia and Europe.
2. the SEACOM/TEAMS wave in 2009, plugging South Africa, Tanzania, Kenya, and Djibouti to Asia and the MENA region.
3. the Main1/Glo1/EASSy wave in 2010, plugging Ghana and Nigeria to Europe, and plugging South Africa, Madagascar, Comoros, Tanzania, Kenya, Somalia, Djibouti and Sudan together.
4. the WACS/ACE wave in 2012, plugging South Africa, Namibia, Angola, the RDC, the Congo, Cameroun, Nigeria, Togo, Ghana, Sierra Leone, Ivory Coast, Cap Verde, Liberia, Benin, Guinea, Gambia, Mauritania to Europe.

Once the treatment is identified, the following equation is estimated:

$$ICT_{i,t}^{j} = \delta_0 + \delta_1 D_t + \delta_2 D^j + \delta_3 D_t^j + \delta_4 X_{i,t} + \varepsilon_{i,t}^{j} \qquad (1)$$

Where *j* indexes the treated and untreated groups, with j=1 for the treatment group (country *i* has been plugged to the global internet by a SMC at time *t*) and j=0 for the control group (country *i* has not been plugged to the Internet by SMC at time *t*). ICT_{it} is the final telecommunication outcome variable, detailed in the next subsection. D_t is a dichotomous variable equal to one since the SMC arrival and zero before the SMC arrival, D^j is a dichotomous variable equal to one if the country *i* is concerned by the SMC arrival and zero otherwise, and D_t^j is a dichotomous variable equal to one when country is treated, zero otherwise. $X_{i,t}$ is a vector of control variables, detailed in the next subsection, and $\varepsilon_{i,t}^{j}$ is an error term. Under the assumption that $E(\varepsilon_{i,t}^{j} | D_t^j) = 0$, the parameter δ_3 is the coefficient identifying the causal effect of the treatment – the SMC arrival – on telecom outcomes. This causal effect is obtained by calculating the DID equal to the change in mean Internet penetration rates for the treatment group minus the change in mean internet penetration rates for the control group. The parameter δ_1 captures how both groups are affected over time by the SMC arrival, and the parameter δ_2 captures the time-invariant difference in Internet penetration rates between the treatment and control groups. We limit the analysis to regional transcontinental SMC arrivals – that is, SMC plugging more than two Sub-Saharan countries to another continent – because these are less likely to be affected by national policies than by regional characteristics, making the treatment less subject to endogeneity concerns.

In a second step, a multivariate regression analysis of the impact of new digital vulnerabilities resulting from SMC deployment on the telecommunication sector is conducted by applying the within fixed-effect estimator to the following specification:

$$ICT_{i,t} = \alpha_0 + \alpha_1.X_{i,t} + \alpha_2.INF1_{i,t} + \alpha_3.INF2_{i,t} + \theta_i + \rho_t + \omega_{i,t} \quad (2)$$

Where $ICT_{i,t}$ is the telecommunication sector's final or intermediary outcome variable in country i and year t; $X_{i,t}$ is a vector of control variables; $INF1_{i,t}$ and $INF2_{it}$ are variables of infrastructure deployment and digital vulnerability, respectively. θ_i is the country fixed effect and ρ_t is the time fixed-effect controlling for unobserved fixed country and time heterogeneity, and $\omega_{i,t}$ an error term. Dependent and independent variables are detailed in the next subsection.

3.2. The data

The data used in the empirical analysis is detailed in this section. Data sources, definitions, descriptive statistics, and cross-correlation coefficients between variables are presented in Appendix A.

Telecommunication sector outcomes (ICT_{it})

Final outcome variables are used as dependent variable in DID estimations, while both final and intermediary outcome variables are used in the multivariate regression analysis. The development of the telecommunication sector (ICT_{it}) is therefore approximated by three final outcomes variables:

- **Outcome 1: the Internet penetration rate** in the population, that is, the share of Internet users in the population. This variable measures Internet access, through mobile Internet or fixed broadband, from Internet café to home-based Internet usage.
- **Outcome 2: the mobile penetration rate**, that is ,the number of mobile cellular subscription per 100 inhabitants. This is a key indicator of the telecom sector development, especially in SSA, since most telecommunications, including Internet ones, pass through this medium.[11]
- **Outcome 3: the share of households with Internet connection**. This Internet penetration variable is more restrictive since it confines Internet access to home-based Internet, mostly relying on fiber/cable/DSL infrastructures.

The internet penetration rate in the population is used as main final outcome variable because it better reflects Internet usage in Africa (access to the Internet via Internet cafés, through smartphone) than the share of households with a Internet subscription, which depends on the wireline infrastructure overage, often lacking in SSA. We also use an indicator of mobile penetration as a final telecommunication outcome variable because Internet penetration rate in SSA strongly relies on mobile phone penetration rates.

In multivariate regression analyses, specified in equation (2), we also use as dependent variable three intermediary outcome variables that further the comprehension of the channels linking digital vulnerabilities to final telecommunication outcomes. In fact, digital vulnerability variables may widen the digital divide by increasing telecommunication tariffs, by reducing the telecommunication sector capacity of providing quality services, and by increasing the telecommunication networks instability:

[11] However, one drawback of this metric is that, because of poor telecommunication regulations and lack of interoperability agreements between operators, people may be incited to buy one mobile per operator to lower communication costs.

- **Channel 1**: **telecommunication tariffs**, proxied by the mobile cellular prepaid connection charge (in USD and logarithm). This mobile prepaid tariff variable is preferred to other tariff variable such as mobile monthly subscription charge because of better data availability, and because it better reflects mobile phone usage in SSA. [12]
- **Channel 2**: **the telecommunication sector capacity**, proxied by the total annual investments in the telecommunication sector (in USD and logarithm).[13]
- **Channel 3**: **the telecommunication network instability**, proxied by the annual number of faults per 100 fixed lines (in logarithm). This variable is of particular interest for the analysis since one direct consequence of digital vulnerabilities is the instability of networks. However, this variable does not fully reflect the over network instability since faults which are not the responsibility of public operators are not recorded (See Appendix A.1).

Infrastructure deployment variables ($INF1_{it}$)

The first set of infrastructure-related variables included in equation (1) consists of variables reflecting the deployment of telecommunication infrastructures addressed in sub-section 2.1. These controls, discussed in section 2.1, are the following:

- The number of SMCs,
- The total number of SMC operators by country,
- The time passed (in years) since the first fiber SMC arrival.

In addition to the above SMC-related control variables, the number of Internet Exchange Points[14] (IXPs) by countries, calculated for a large number of countries over a long period, is also included in equation (2) as a proxy of the terrestrial infrastructure deployment.

Digital vulnerability variables ($INF2_{it}$)

Variables of digital vulnerability, discussed in the previous section, and explaining the development of the digital economy are the following:

- **The digital isolation:** alternatively approximated by the geographic, capital, or demographic distances to SMC landing stations.
- **The experience of SMC outages**: this shock variable is the annual number of SMC outages that have affected Internet traffic in Sub-Saharan African countries, described in table 2. Details on these events are provided in Appendix B.4.
- **The risk of SMC outages induced by seismic activity**: this risk variable is the annual frequency of seaquakes above 5 on the Richter scale that occurred within a100km, 500km, and 10000km radius from SMC landing station, alternatively.

Appendix A.4 displays low cross-correlations between these variables, suggesting they reflect distinct sources of digital vulnerability.

[12] Moreover, one statistical drawback of using monthly subscription variable is that, if prepaid services are mostly used, as in SSA countries, the monthly subscription charge variable is set to zero (ITU, 2010).

[13] We chose the investment variable to proxy the telecom sector performance rather than the telecommunication sector's revenue, because the latter may reflect operators and ISPs' higher revenues derived from with a monopoly position which often leads to low service quality, high tariffs, and infrastructure under-exploitation (Sutherland, 2014).

[14] IXPs are Internet hubs that permit to reduce communication latency, by promoting direct interconnections between countries, and to save bandwidth through an efficient allocation of local, regional and international traffic. IXPs also allow the sharing of Internet and other communications traffic at low cost, which in turn reduces the cost of telecommunication services. Therefore, the IXPs network is therefore a central element for the development of local and regional Internet ecosystems (Malecki, 2002; Weller and Woodcock, 2013; OECD, 2014).

Other control variables (X_{it})

Other control variables are the logarithm of GDP *per capita*, the share of the population between 15 and 64-years old, the share of the urban population, the degree of democracy, the secondary education index, the share of the population having access to electricity.[15] DID estimations of equation (1), because they include fixed effect components, also control for landlockedness and the country's area in squared-kilometers. Information on variable sources, definitions, summary statistics, and cross-correlations is provided in Appendix A.

4. Empirical results

This section presents the difference-in-differences (DID) estimations of SMC arrival on the telecom sector final outcomes (equation (1)). Then, multivariate estimations of equation (2) are conducted to highlight the interplay between different sources of digital vulnerability and the development of the telecom sector in SSA.

4.1. Impact of SMC arrivals on ICT penetration rates in SSA: DID estimations

The DID approach followed in this paper considers the various waves of SMC arrivals in SSA as different treatments likely to impact the development of the telecom sector in the sub-region.

SMC regional arrivals and the parallel trend assumption

One critical assumption of DID estimator is the parallel trend assumption, which requires outcome variables to follow parallel trends in the absence of the treatment, in our case, SMC arrivals. Without information on what would have happened without treatment, one common practice is to check the existence of parallel trend before the treatment. To check whether this assumption holds for telecommunication outcomes (TIC_{it}), figures 9 and 10 plot the co-evolution of these outcomes for treatment and control groups related to waves 2 and 3, between 2002 (after wave 1) and 2012 (before wave 4). The co-evolution of these outcomes related to waves 1 and 4 are reported in Appendix C but are not considered in the analysis because the treatment seems to have a low influence on telecommunication outcomes for these two waves.[16] In figure 10, SEACOM/TEAMS and the Main1/Glo1/EASSy waves are considered as one single treatment because they occurred from one year to another.

The visual inspection of these graphs stresses that the following outcomes exhibits parallel trends between treatment and control groups, before the treatment date: the share of population using the Internet, the share of households with Internet connection, and the mobile penetration rate. Among these three outcomes, Internet penetration rates among households and the population seem to have been strikingly and positively impacted by waves 2 and 3 of SMCs (Figure 10), despite showing apparent divergent pre-trends when taking the SEACOM/TEAMS wave 2 alone (Figure 9). By contrast, these waves of SMCs do not seem to have impacted the penetration of mobile phones, which is not very surprising since the mobile phone in SSA has in some way leapfrogged the deployment of infrastructures (Aker and Mbiti, 2010). The following DID analysis will therefore focus on the impact of waves 2 and 3 taken together, taking waves 2 as benchmark, on Internet penetration rates.

[15] This last variable being documented sporadically, missing data are replaced by five-year moving averages. When a five-year average cannot be calculated, we use the previous five-year average value.

[16] Contrary to other cables, ACE has been slowly expanding trough time, maybe explaining why telecommunication outcomes are not very responsive to its deployment.

Figure 9. Trend comparison of telecom outcomes between treatment and control groups – SMC Wave 2.

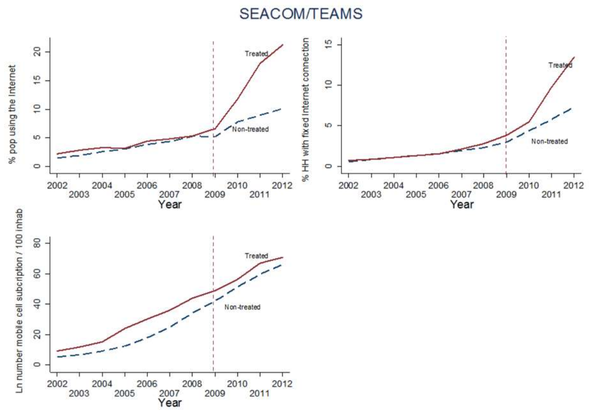
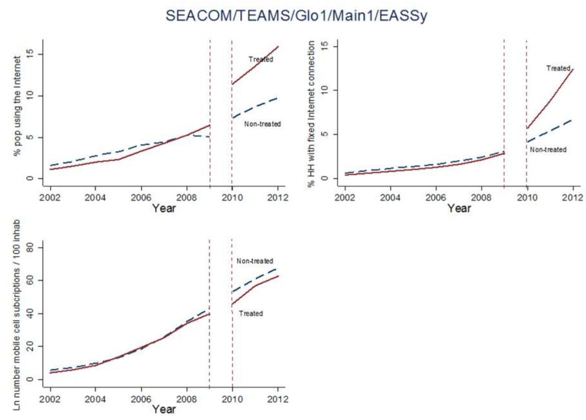


Figure 10. Trend comparison of telecom outcomes between treatment and control groups – SMC Wave 2 & 3.



DID estimations

Table 3 and 4 report DID-estimates associated with the second and third waves of SMC-laying, respectively. DID estimations are run over the sample of 46 SSA countries (sample A), the same sample excluding South-Africa and Nigeria (sample B), and excluding landlocked countries (sample C). South Africa and Nigeria are excluded because regional SMCs might have been deployed to connect these major demographic and economic centers to the rest of sub-Saharan African countries, which therefore would make the treatment endogenous. Landlocked countries are also excluded because they cannot directly host SMCs. This geographic feature makes them particularly dependent on their neighboring coastal countries receiving SMCs, so that the treatment might act in a different way in these countries. We also conduct DID estimations over the 2002-2012 sub-period and the whole 1990-2014 period. The 2002-2012 is the sub-period of interest since it excludes the laying of other regional SMCs preceding or following the SMC under study[17]. In table 4, the 2009 SEACOM-TEAMS wave and the 2010 EASSy-Glo1-Main1 wave are considered together as a single wave, due to their possible confounding effect on Internet penetration rate evolution.

[17] Between 2002 and 2012, three waves of SMCs with minor impact of SSA's connectivity (plugging less than three countries) have occurred. In 2003, the SAS-1 connected Sudan to Saudi Arabia. In 2006, the Falcon connected Sudan to the Middle-East and India. In 2011, the EIG connected Djibouti to Europe and to the Arabian Peninsula, while the SAS-2 connected Sudan to Saudi Arabia.

Results in table 3 support that the SEACOM-TEAMS cables had a strong, positive and significant impact on Internet penetration rates. First, they stress that this wave has led to an approximate 6 percentage-point increase in the share of population using the Internet, when considering the 2002-2012 period and the sample of SSA countries and SSA coastal countries. These estimates do not markedly differ from those obtained from DID estimations over the 1990-2014 period. Second, excluding South Africa and Nigeria lowers the impact of SMC deployment in the remaining SSA countries, corresponding to a 3-4 percentage point increase in the share of population using the Internet. This suggests that the impact of SMC deployment in these two countries has been subsequently stronger than in other sub-Saharan African countries, or that a reverse causality bias inflates estimated relationships.[18] Third, the estimate holds when the sample is limited to African coastal countries, suggesting that SMC arrivals on the African littoral also had a strong impact in landlocked countries, probably by reducing their international digital isolation. Fourth, the impact of the SEACOM-TEAMS wave on the share of households with Internet connection is also significant, but softer and not robust to the exclusion of South Africa and Nigeria from the sample. This evidence of a softer and less robust effect of this SMC deployment on the penetration of Internet among households can be explained by the lacking last-mile wireline infrastructures required to bring fixed Internet to African homes.

Table 3. DID in Internet penetration rates, before and after wave 2 (SEACOM-TEAMS).

	DID parameters (δ_3)	**# observations**	**# treated/control obs**	**R-squared**
	Period 2002-2012			
	% population using the Internet			
Sample A : SSA	6.059*** (4.71)	441	44/397	0.48
Sample B: SSA excl. ZAF and NGA	3.318*** (2.79)	419	33/386	0.46
Sample C: SSA excl. landlocked countries	6.033*** (4.32)	288	44/244	0.53
	% HH with Internet connection			
Sample A : SSA	3.482*** (4.04)	371	44/327	0.50
Sample B: SSA excl. ZAF and NGA	0.416 (0.49)	349	33/316	0.47
Sample C: SSA excl. landlocked countries	3.268** (3.27)	254	44/210	0.52
	Period 1990-2014			
	% population using the Internet			
Sample A : SSA	7.222*** (7.55)	760	79/681	0.49
Sample B: SSA excl. ZAF and NGA	3.903*** (4.37)	719	56/663	0.48
Sample C: SSA excl. landlocked countries	7.294*** (6.88)	498	79/419	0.51
	% HH with Internet connection			
Sample A : SSA	3.484*** (4.05)	373	44/329	0.50
Sample B: SSA excl. ZAF and NGA	0.417 (0.50)	396	33/351	0.47
Sample C: SSA excl. landlocked countries	3.289*** (3.31)	256	44/212	0.52
Controls	Ln GDP/cap, % 15-64 yrs-old pop, % of urban pop, % pop with electricity access, 2ndary educ index, Democracy, area in km2, landlockedness			

t-student in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard-errors robust to heteroscedasticity.

[18] This impact on Internet penetration could be higher because of a better terrestrial infrastructure coverage, a more educated population, or a higher population density (especially in Nigeria). For the same reasons, Nigeria and South Africa exhibit a ‘digital maturity’ that could justify the deployment of SMC, thereby leading to a reverse causality bias.

However, considering the second and third SMC waves together, DID estimations in table 4 support that SMCs arrivals had a strong and robust effect on Internet penetration in the population and also on Internet penetration among households. Estimates support that these two SMC waves have increased by around 7-8 percentage points the share of population using the Internet, and by 4-5 percentage points the share of households with Internet connection. These relationships are robust to the exclusion of South Africa and Nigeria from the sample, though the estimated effect on the sample without South Africa and Nigeria is again half softer than estimates obtained from the whole sample. Again, estimations conducted over the 2002-2012 period provide estimates that are quite close to those associated with the 1990-2014 period.

To conclude this first empirical section, DID estimations stress that the arrival of SMCs in 2009 and 2010 had a robust, significant and positive impact on Internet penetration rates in SSA. The next section furthers the analysis of the consequences of SMC arrivals on the internet economy by highlighting the impact of structural digital vulnerabilities related to their deployment.

Table 4. DID in Internet penetration rates, before and after waves 2 & 3 (SEACOM-TEAMS-Glo1-Main1-EASSy).

	DID parameters (δ_3)	# observations	# treated/control obs	R-squared
	Period 2002-2012			
	% population using the Internet			
Sample A : SSA	7.990*** (7.59)	360	52/290	0.58
Sample B: SSA excl. ZAF and NGA	4.131*** (4.03)	342	61/290	0.49
Sample C: SSA excl. landlocked countries	8.244*** (7.07)	235	70/165	0.63
	% HH with Internet connection			
Sample A : SSA	5.343*** (7.50)	305	68/237	0. 61
Sample B: SSA excl. ZAF and NGA	4.217*** (6.21)	287	50/237	0.60
Sample C: SSA excl. landlocked countries	5.369*** (6.21)	209	68/141	0.62
	Period 1990-2014			
	% population using the Internet			
Sample A : SSA	9.134*** (12.28)	720	144/576	0.57
Sample B: SSA excl. ZAF and NGA	4.658*** (6.47)	681	105/576	0.51
Sample C: SSA excl. landlocked countries	9.630*** (11.47)	472	144/328	0.60
	% HH with Internet connection			
Sample A : SSA	5.449*** (8.19)	339	76/263	0.61
Sample B: SSA excl. ZAF and NGA	4.321*** (6.82)	319	56/263	0.60
Sample C: SSA excl. landlocked countries	5.520*** (6.85)	234	76/158	0.62
Controls	Ln GDP/cap, % 15-64 yrs-old pop, % of urban pop, % pop with electricity access, 2ndary educ index, Democracy, area in km2, landlockedness			

t-student in parenthesis. $p < 0.1$, $^{**} p < 0.05$, $^{***} p < 0.01$. Standard-errors robust to heteroscedasticity.

4.2. Infrastructure deployment, digital vulnerability and the telecommunication sector development in SSA

The first round of OLS and FE estimations in tables 5 and 6 shows that infrastructure deployment variables are significant determinants of the telecommunication sector development. First, estimations in table 5 show that including telecom infrastructure deployment variables strongly raises the explanatory power of regressions (columns (3) and (6)). Second, estimations highlight the positive and significant contribution of the deployment of SMCs and IXPs. Interestingly, estimated coefficients of the effect of SMC deployment on Internet penetration (table 5, columns (3) and (6)) lie within the same range as previous DID estimates (resulting from the restricted sample excluding Nigeria and South Africa), thereby supporting the consistency of estimated relationships. Third, estimations also point to the negative and significant contribution of the number of SMC owners to Internet penetration rates. The number of SMC owners being related to the extent of fixed cost sharing for SMC deployment, this negative relationship may be explained by the necessity for telecom operators of sharing fixed costs to deploy costly SMCs in less mature Internet markets. In table 6, FE estimations show that among intermediary telecom outcome variables, only telecom investment is significantly influenced, with the expected sign, by infrastructure deployment variables (column (6)): positively with the number of SMC, and negatively with the number of SMC owners. In other words, SMC and IXP deployment is associated with higher investment in telecommunication and with a significant increase in Internet and mobile phone penetration, but unrelated to a change in communication tariffs or to greater telecommunication network stability.

Table 5. Infrastructure deployment and the telecom sector in SSA, *within* fixed-effect panel estimations.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	% pop using the Internet			**% HH with Internet**			**# of mobile subscript / 100 inhab.**		
	OLS	FE	FE	OLS	FE	FE	OLS	FE	FE
Ln GDP/cap	0.461*	2.558	-0.333	1.459***	5.651*	0.204	5.334***	-0.504	-5.196
	(1.69)	(0.80)	(-0.14)	(4.52)	(1.88)	(0.09)	(5.91)	(-0.09)	(-1.09)
% of 15-24yrs	0.420***	1.131**	1.293**	0.508***	1.328***	1.545***	0.925***	3.053**	2.947**
	(3.90)	(2.18)	(2.60)	(5.78)	(3.16)	(4.10)	(2.95)	(2.63)	(2.56)
% urban pop	-0.050***	0.213	0.172	-0.099***	-0.723	-0.567*	0.129**	3.044**	2.704**
	(-3.78)	(0.65)	(0.60)	(-5.95)	(-1.63)	(-1.78)	(2.31)	(2.41)	(2.10)
Democracy	-0.171	-0.113	0.446	-0.342	-1.356	-0.592	-0.561	2.389	4.419
	(-0.76)	(-0.14)	(0.79)	(-1.43)	(-1.50)	(-0.81)	(-0.73)	(0.75)	(1.60)
2^{ary} Education	0.0179	-0.147	-0.142	-0.032*	-0.289**	-0.297***	0.107**	-0.777**	-0.818***
	(1.09)	(-1.26)	(-1.40)	(-1.88)	(-2.51)	(-3.03)	(2.06)	(-2.27)	(-2.96)
Electricity	0.062***	-0.0448	-0.132	0.059***	-0.0481	-0.0629	-0.00977	0.838	0.576
access (%)	(5.13)	(-0.30)	(-1.03)	(4.38)	(-0.49)	(-0.86)	(-0.23)	(1.35)	(1.04)
Infrastructure deployment									
# SMCs			3.450***			2.852***			-2.249
			(2.88)			(3.25)			(-0.70)
# years since			0.312*			0.440**			1.808***
1st SMC			(1.77)			(2.10)			(3.33)
# IXPs			3.527***			2.462*			4.711
			(3.13)			(1.92)			(1.37)
# SMC owners			-0.226**			-0.273*			0.165
			(-2.29)			(-1.91)			(0.45)
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	778	778	778	418	418	418	818	815	818
# countries	46	46	46	44	44	44	46	46	46
R^2 (within)	0.539	0.533	0.665	0.609	0.563	0.685	0.770	0.819	0.847

t-student in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard-errors robust to heteroscedasticity.

Table 6. Infrastructure deployment and the telecom sector in SSA, *within* fixed-effect panel estimations.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Prepaid mobile cell connect charge			**Telecom investment**			**# of fixed line faults**		
	OLS	FE	FE	OLS	FE	FE	OLS	FE	FE
Ln GDP/cap	-0.531***	-2.057	-1.902	0.172	-0.195	-0.553	-0.173*	-0.629	-0.648
	(-3.55)	(-1.25)	(-0.98)	(1.07)	(-0.23)	(-0.78)	(-1.74)	(-1.23)	(-1.24)
% of 15-24yrs	0.0279	0.393*	0.398*	-0.0571*	-0.0828*	-0.0596	-0.0024	-0.0944	-0.103+
	(0.92)	(1.76)	(1.81)	(-1.94)	(-1.69)	(-1.04)	(-0.12)	(-1.36)	(-1.62)
% urban pop	0.00568	-0.231*	-0.231*	-0.021***	-0.0070	0.0223	-0.0005	0.0523	0.0675
	(0.78)	(-1.88)	(-1.92)	(-2.91)	(-0.12)	(0.57)	(-0.12)	(0.62)	(0.83)
Democracy	0.296**	0.214	0.182	0.220*	0.0475	0.0395	0.179**	0.0292	0.0580
	(2.29)	(0.96)	(0.83)	(1.79)	(0.21)	(0.19)	(2.04)	(0.12)	(0.22)
2^{ary} Education	0.0135*	0.0411	0.0343	0.0175**	-0.0043	0.00358	0.0061	-0.0011	-0.0008
	(1.79)	(1.64)	(1.33)	(2.36)	(-0.31)	(0.28)	(1.37)	(-0.07)	(-0.05)
Electricity access (%)	0.00817	-0.0223	-0.0182	0.00934	-0.0463*	-0.0482**	0.0010	-0.0422	-0.0423
	(1.43)	(-0.86)	(-0.73)	(1.27)	(-1.79)	(-2.17)	(0.26)	(-0.91)	(-0.97)
Infrastructure deployment									
# SMCs			0.0577			0.953**			0.0461
			(0.15)			(2.24)			(0.18)
# years since 1st SMC			-0.229			-0.0536			0.0212
			(-0.70)			(-1.60)			(0.43)
# IXPs			0.0143			0.112			-0.328
			(0.37)			(0.40)			(-1.29)
# SMC owners			-0.0306			-0.0753**			-0.0123
			(-0.39)			(-2.08)			(-0.53)
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	240	240	240	494	494	494	381	381	381
# countries	44	44	44	44	44	44	46	46	44
R^2 (within)	0.328	0.430	0.436	0.226	0.377	0.437	0.435	0.544	0.552

t-student in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard-errors robust to heteroscedasticity.

SMC exposure to seismic risk

The second round of estimations highlights the impact of the maritime infrastructure exposure to seismic risk, and is reported in tables 7 and 8. The variable of annual frequency of seaquakes in the neighborhood of SMC landing stations is computed according to three different radiuses: a 1000km, a 500km and a 100km radius from SMC landing stations. Results put in evidence the negative impact of this source of digital vulnerability on telecom sector development, especially when the radius is set at 500km from SMC landing stations. With this calibration, the exposure to seismic risk is found to negatively affect Internet penetration rates, mobile penetration rate, and telecom investment; and to have a positive and 5%-significant effect on mobile-cellular connection charges, and a positive 15% significant effect on fixed-line phone faults. This last effect gets 5%-significant when the radius is extended to 1000km from SMC landing stations, corroborating Carter et al. (2009)'s observation according to which, in 2006, almost one-third of cable breaks occur in deep-sea water (probably more today, given the dramatic densification of the undersea cable network). Nonetheless, it is worth reminding that the network instability variable is focused on the number of fixed phone line faults under the responsibility of public operators, and therefore does not take into account disturbances of the cellular network and those incurred on private operator networks (see variable's definition in Appendix A.1). This variable therefore partially reflects the overall network instability, including the instability caused by seismic events.

Table 7. SMC exposure to seismic risk and the telecom sector development in SSA, *within* fixed-effect panel estimations (1/2).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	% pop using the Internet			% HH with Internet			# of mobile subscript / 100 inhab.		
Seaquake freq 1000km rad.	-0.129 (-1.23)			-0.107 (-1.51)			-0.315 (-0.53)		
Seaquake freq 500km rad.		-0.272^{**} (-2.53)			-0.116^{**} (-2.45)			-1.349^{***} (-3.19)	
Seaquake freq 100km rad.			-0.247^{**} (-2.36)			-0.0959^{*} (-1.70)			-1.149^{***} (-2.97)
Controls	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	778	778	778	418	418	418	818	818	818
# countries	46	46	46	44	44	44	46	46	46
R^2 (within)	0.666	0.667	0.666	0.686	0.686	0.685	0.847	0.849	0.848

t-student in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard-errors robust to heteroscedasticity. Control estimates not reported in the table.

Table 8. SMC exposure to seismic risk and the telecom sector development in SSA, *within* fixed-effect panel estimations (2/2).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Prepaid mobile cell connect charge			Telecom investment			# of fixed line faults		
Seaquake freq 1000km rad.	-0.0445 (-0.69)			0.0364 (0.61)			0.0833^{**} (2.05)		
Seaquake freq 500km rad.		0.295^{*} (1.71)			-0.170^{*} (-1.91)			0.137 (1.54)	
Seaquake freq 100km rad.			0.727^{***} (12.30)			-0.095 (-1.24)			0.135 (1.07)
Controls	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	240	240	240	494	494	494	381	381	381
# countries	44	44	44	44	44	44	44	44	44
R^2 (within)	0.437	0.442	0.445	0.437	0.439	0.437	0.554	0.553	0.552

t-student in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard-errors robust to heteroscedasticity. Control estimates not reported in the table.

SMC outages

In a third step, having studied the seismic-induced risk of SMC outages, the analysis now turns to the actual experience of SMC outages. Tables 9 and 10 report the results when the shock variable of annual frequency of SMC outages is introduced in the regression equations. Estimates in columns (1), (4), (7) in each table do not provide evidence of a significant impact of SMC outages on telecommunication outcomes. This lack of evidence could first be explained by differences in the resilience of the maritime infrastructure network to SMC outages, which in turn depends on available and functioning SMCs through which telecommunication traffic could be rerouted when cable breaks occur. A second explanation is the possible lagging effect of SMC outages on telecommunication outcomes.

First, to account for the resilience of the infrastructure network, equation (2) is augmented by adding an interaction term between the SMC outage variable and the number of SMC variable. [19] Estimates

[19] By estimating:
$$TIC_{i,t} = \alpha_0 + \alpha_1 . X_{i,t} + \alpha_2 . INF1_{i,t} + \alpha_3 . SMC\ outages_{i,t} + \alpha_4 . [SMC\ outages \times SMC\ number]_{it} + \theta_i + \rho_t + \omega_{i,t}$$

are reported in columns (2), (4), (6) of tables 9 and 10, and stress that SMC outages have a negative impact on Internet penetration when controlling for the dampening effect of the number of SMC (table 9 column (2)). It is also found to reduce instability of the wireline telecommunication network following SMC outages (table 10 column (8)).

Second, to account for the persistent lagging effect of SMC outages on telecommunication outcomes, one-year and two-year lags of this shock variable have been included in the regression. Estimates in table 9 support a strong and significant negative effect of lagged SMC outages on Internet penetration among households and on mobile penetration rates. In particular, they stress that one SMC outage in the past two years leads to two percentage point decrease in Internet penetration rate, and reduces by 10 the number of mobile subscriptions per 100 inhabitants. The mechanisms underlying these effects are not clearly identified, as evidence of a lagging effect of SMC outages on intermediary outcome variables is lacking (Table 10).

Table 9. SMC outages, resilience, and the telecom sector development in SSA, within fixed-effect panel estimations (1/2).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	% pop using the Internet			**% HH with Internet**			**# of mobile subscript / 100 inhab.**		
SMC outages	0.490	-1.959*	0.708	-0.800	0.230	-0.771	-3.207	-5.065	-1.411
	(0.31)	(-1.91)	(0.42)	(-1.63)	(0.53)	(-1.41)	(-1.06)	(-1.50)	(-0.47)
SMC outages × # SMCs		1.872**			-0.751			1.414	
		(2.27)			(-1.34)			(0.69)	
SMC outages – Lag 1			0.091			-1.878**			-5.540
			(0.05)			(-2.57)			(-1.21)
SMC outages – Lag 2			-0.846			-2.231***			-10.536***
			(0.05)			(-2.74)			(-2.59)
Controls	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	778	778	778	418	418	418	818	818	818
# countries	46	46	46	44	44	44	46	46	46
R^2 (within)	0.665	0.671	0.665	0.686	0.689	0.695	0.847	0.848	0.849

t-student in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard-errors robust to heteroscedasticity. Control estimates not reported in the table.

Table 10. SMC outages and resilience of the telecom sector development in SSA, within fixed-effect panel estimations (1/2).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Prepaid mobile cell connect charge			**Telecom investment**			**# of fixed line faults**		
SMC outages	-0.0044	-0.306	-0.105	-0.003	0.421	-0.037	-0.654	0.208	-0.674
	(-0.02)	(-1.46)	(-0.34)	(-0.01)	(1.29)	(-0.14)	(-1.41)	(0.38)	(-1.34)
SMC outages × # SMCs		0.163			-0.277			-0.465**	
		(1.06)			(-1.38)			(-2.52)	
SMC outages – Lag 1			-0.130			-0.017			-0.471
			(-0.35)			(-0.06)			(-0.94)
SMC outages – Lag 2			0.090			0.120			-0.373
			(0.17)			(0.32)			(-1.17)
Controls	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	240	240	240	494	494	494	381	381	381
# countries	44	44	44	44	44	44	44	44	44
R^2 (within)	0.436	0.437	0.436	0.437	0.440	0.437	0.556	0.560	0.558

t-student in parenthesis. $^{+}p < 0.15$ * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard-errors robust to heteroscedasticity. Control estimates not reported in the table.

Digital isolation

In a fourth step, the contribution of digital isolation variables is studied. Tables 11 and 12 highlight the contribution of digital isolation, approximated by three distance variables: the demographic distance, the geographic distance and the capital distance to SMC landing stations. Compared to previous estimations, including digital isolation variables in the regressions using Internet penetration rates (table 11, columns(1) to (6)) and the number of faults per 100 fixed-lines (table 12, columns (7) to (9)) as dependent variables leads to a strong increase in their explanatory power. Among digital isolation variables, demographic distance appears as the most significant and most relevant proxy, but geographic distance is found to have a stronger effect on Internet penetration in the population (table 11, column (2)), on telecommunication tariffs (table 12, column (2)) and on the number of fixed line faults (table 12, column(8)). Demographic distance is however found to significantly reduce the number of mobile subscriptions per 100 inhabitants, which geographic distance does not. Moreover, all digital isolation proxies are found to significantly contribute to the telecommunication network instability. Therefore, this bunch of evidence suggests that digital isolation is an important source of a country's digital divide, and critical dimension of a country's digital vulnerability.

Table 11. Digital isolation and ICT development in SSA, *within* fixed-effect panel estimations (1/2).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	% pop using the Internet			**% HH with Internet**			**# of mobile subscript / 100 inhab.**		
Ln demo distance	-0.794**			1.110			-3.115**		
	(-2.05)			(1.39)			(-2.08)		
Ln geo distance		-0.854**			0.822			-2.548	
		(-2.05)			(0.75)			(-1.43)	
Ln capital distance			0.313			0.348			-0.271
			(1.34)			(1.60)			(-0.39)
Controls	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	703	702	699	381	381	382	735	734	731
# countries	44	44	46	44	44	44	44	44	46
R^2 (within)	0.735	0.735	0.708	0.736	0.733	0.743	0.864	0.863	0.872

t-student in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard-errors robust to heteroscedasticity. Control estimates not reported in the table.

Table 12. Digital isolation and ICT development in SSA, *within* fixed-effect panel estimations (2/2).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Prepaid mobile cell connect charge			**Telecom investment**			**# of fixed line faults**		
Ln demo distance	0.594**			0.0322			0.365***		
	(2.49)			(0.28)			(4.30)		
Ln geo distance		0.816***			0.0820			0.383***	
		(3.05)			(0.68)			(3.71)	
Ln capital distance			0.0598			-0.0811			0.0884*
			(0.50)			(-1.40)			(1.71)
Controls	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	215	214	218	432	431	433	323	323	334
# countries	42	41	42	41	40	41	42	42	42
R^2 (within)	0.438	0.446	0.446	0.456	0.457	0.457	0.603	0.602	0.592

t-student in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard-errors robust to heteroscedasticity. Control estimates not reported in the table.

5. Concluding remarks

This paper opens new perspectives for the economic literature on the benefits and risks of the increasing digitalization of economies, especially developing economies. It provides new insights into the telecom infrastructure's contribution to the telecom sector in SSA, but also underlines the vulnerability of SSA to failures in its telecommunication network. In fact, while the deployment of the SMC has in average strongly stimulated the ICT sector in SSA, this sector's development is still exposed to SMC outages and hampered the digital isolation of countries and populations remote from SMC landing stations.

In a first step, a diff-in-diff approach has been followed to study the impact of SMC waves that landed in SSA on the development of the ICT sector. Among these different waves, the impact of the 2009 SEACOM/TEAMS and the 2010 Glo1/Main1/EASSy waves could be studied within DID estimation framework. Results stress that their arrival is associated with a 7-8 percentage point increase in Internet penetration rates, mostly driven by South Africa and Nigeria. Once excluding these two countries from the sample, this impact remains significant but falls to 3-4 percentage points. Moreover, excluding landlocked countries does not affect the strength and significance of coefficients, suggesting that the arrival of SMCs has been beneficial to both coastal and landlocked countries, probably by reducing the latter's digital isolation.

The issue of digital vulnerability related to the deployment of SMCs is then studied within a panel fixed-effect estimation framework. First, results stress that considering digital vulnerability variables, especially digital isolation, strongly increases the explanatory power of regressions. Second, digital isolation, proxied by the demographic-centroid distance to SMC landing stations, has negative and significant impact on Internet and mobile penetration rates, and a positive and significant impact on mobile subscription charge and on the annual number of faults per 100 fixed-lines. Third, the role of the infrastructure exposure to seismic activity is also found to be significant, as the annual frequency of seaquakes in the neighborhood of SMCs has a negative impact on Internet and mobile penetration rates, on telecom investment, and a positive impact on mobile subscription charge and network instability. Fourth, estimations also point to the negative and lasting impact of SMC outages on Internet penetration rates, especially in countries relying on few SMCs. This last result therefore points out that hosting a large number of SMCs not only increase Internet traffic, speed and capacity, but also lower the countries' vulnerability to cable outage and therefore increase the telecom network's resilience.

All in all, by highlighting the ambiguous effects of SMC deployment in SSA, this paper is somewhat related to Malecki (2002, p.399)'s view on the geography of the Internet infrastructure, who stressed that "interconnection is both critical to the functioning of the Internet and the source of its greatest complications".

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Appendices

A. Variables' sources, definition, and descriptive statistics.

A.1. Variable sources and definitions

Variable	Source	Definition
% pop using Internet	ITU	Percentage of individuals using the Internet
% HH with Internet	ITU	Percentage of households with Internet connection
Ln # mobile subscript	ITU/World Bank	Mobile cellular telephone subscriptions are subscriptions to a public mobile telephone service that provide access to the PSTN using cellular technology. The indicator includes (and is split into) the number of postpaid subscriptions, and the number of active prepaid accounts (i.e. that have been used during the last three months). The indicator applies to all mobile cellular subscriptions that offer voice communications. It excludes subscriptions via data cards or USB modems, subscriptions to public mobile data services, private trunked mobile radio, telepoint, radio paging and telemetry services.
Ln mobile-cell prepaid connection charge	ITU	The initial, one-time charge for a new subscription. Refundable deposits should not be counted. Although some operators waive the connection charge, this does not include the cost of the Subscriber Identity Module (SIM) card. The price of the SIM card should be included in the connection charge (for a prepaid service the cost of SIM is equivalent to connection charge). It should also be noted if free minutes or free SMS are included in the connection charge. Taxes should be included. If not included, it should be specified in a note including the tax rate applicable.
Ln telecom invest	ITU	
Fixed line faults	ITU	The total number of reported faults to fixed telephone lines for the year. Faults, which are not the direct responsibility of the public telecommunications operator, should be excluded. This is calculated by dividing the total number of reported telephone faults for the year by the total number of fixed lines in operation and multiplied by 100. The number of faults per 100 fixed lines per year should reflect the total reported by all PSTN service providers in the country.
Ln GDP/cap	World Bank	GDP per capita in 2005 constant USD
% of 15-24yrs	World Bank	Population ages 15-64 (% of total)
% urban pop	World Bank	Urban population (% of total)
Democracy status	Freedom House	1=not free ; 2= partly free; 3= free
2^{ary} Education index	Ferdi/UNDP	Gross secondary school enrolment ratio. According to the UNDP, this indicator measures the number of pupils enrolled in secondary schools, regardless of age, expressed as a percentage of the population in the theoretical age group for the same level of education. Missing raw data has been filled through linear interpolation and extrapolation, and transformed into an index between 0 and 1 by a minmax procedure (Goujon & Feindouno, 2016).
Electricity access (%)	World bank	Percentage of population with access to electricity. Electrification data are collected from industry, national surveys and international sources. Missing data has been inter- and extrapolated using five-year

		moving average.
# SMCs	Author, Telegeography	Number of submarine cables laid in a given country
# IXPs	Author Telegeography, Author, Packet Clearing House and Peering DB.	Number of internet exchange point built in a given country
# SMC owners	Author, Telegeography	Summation of SMC owners associated with cables laid in a given country
# years since 1st SMC*	Author, Telegeography	Number of years passed since first fiber optic SMC arrival.This variable is forward looking, so negative values mean the country is *t* year(s) before SMC arrival.
Ln geo distance	Author, Telegeography	The geographic distance is the country's centroid distance to the closest SMC landing station. When countries have no SMCs (such as landlocked countries), the distance to the closest neighbour's SMC landing station is taken.
Ln demographic distance	Author, Telegeography	The demographic distance is the country's centroid distance, weighted by the spatial distribution of the population, to the closest SMC landing station. When countries have no SMCs (such as landlocked countries), the demographic distance to the closest neighbour's SMC landing station is taken.
Ln capital distance	Author, Telegeography	The capital distance is the country's capital distance to the closest SMC landing station. When political capital differ from economic capital, the economic capital is taken as reference. When countries have no SMCs (such as landlocked countries), the distance to the closest neighbour's SMC landing station is taken.
Seaquake freq 500km rad.	Author, Telegeography, Northern California Earthquake Data Center	Annual number of seaquake above 5 on the Richter scale within a 500km radius from a country's SMC landing station
Seaquake freq 100km rad.	Author, Telegeography, Northern California Earthquake Data Center	Annual number of seaquake above 5 on the Richter scale within a 1000km radius from a country's SMC landing station
Seaquake freq 1000km rad.	Author, Telegeography, Northern California Earthquake Data Center	Annual number of seaquake above 5 on the Richter scale within a 100km radius from a country's SMC landing station
SMC outages	Author	Annual number of SMC outages reported on the web.

A.2. Descriptive statistics

Variable	Mean	Std. Dev.	Min	Max	Obs.	Countries
% pop using Internet	3.599857	6.634304	0	47.076	778	46
% HH with fixed Internet	3.090524	5.706059	0	41.92	412	44
Ln # mobile subscript	20.88281	29.6036	0	179.4714	773	46
Ln mobile-cell prepaid subscript charge	2.267642	1.357488	0	9.720285	235	44
Ln telecom invest	17.45	1.9881	11.3262	27.06795	462	44
Fixed line faults	3.479371	1.341012	0.0295588	7.06732	351	44
Ln GDP/cap	6.592359	1.098209	4.62277	9.53892	778	46
% of 15-24yrs	54.16216	4.352466	47.40301	71.45077	778	46
% urban pop	37.24095	16.49959	7.211	86.4576	778	46
Democracy status	2.105398	0.7187123	1	3	778	46
2^{ary} Education index	28.79894	23.35361	0	100	778	46
Electricity access (%)	34.34615	24.96251	0.5558459	100	778	46
# SMCs	0.3881748	0.8510507	0	6	778	46
# IXPs	0.2172237	0.5372713	0	6	778	46
# SMC owners	4.46144	8.961475	0	59	778	46

# years since 1st SMC*	-1.661954	5.836037	-17	18	778	46
Ln demographic distance	6.627677	1.353204	0	8.558235	703	45
Ln geo distance	6.7562	1.208164	0	8.566905	702	44
Ln capital distance	5.912122	2.573306	0	8.557826	699	46
Seaquake freq 500km rad.	0.0989717	0.9662111	0	25	778	46
Seaquake freq 100km rad.	0.0488432	0.8744507	0	24	778	46
Seaquake freq 1000km rad.	0.3791774	1.546842	0	28	778	46
SMC outages	0.0257069	0.1583614	0	1	778	46

* This variable is forward looking, so negative values mean the country is *t* year(s) before SMC arrival.

A.3 Sample composition

Country Code	Freq. obs	Percent	Country Code	Freq. obs	Percent
AGO	17	2.19	MDG	17	2.19
BDI	18	2.31	MLI	17	2.19
BEN	17	2.19	MOZ	17	2.19
BFA	17	2.19	MRT	16	2.06
BWA	18	2.31	MUS	17	2.19
CAF	17	2.19	MWI	16	2.06
CIV	18	2.31	NAM	18	2.31
CMR	16	2.06	NER	17	2.19
COG	17	2.19	NGA	17	2.19
COM	16	2.06	RWA	16	2.06
CPV	16	2.06	SDN	15	1.93
DJI	18	2.31	SEN	18	2.31
ERI	14	1.8	SLE	18	2.31
ETH	18	2.31	STP	13	1.67
GAB	17	2.19	SWZ	18	2.31
GHA	18	2.31	SYC	16	2.06
GIN	18	2.31	TCD	16	2.06
GMB	18	2.31	TGO	18	2.31
GNB	16	2.06	TZA	17	2.19
GNQ	16	2.06	UGA	18	2.31
KEN	18	2.31	ZAF	18	2.31
LBR	14	1.8	ZMB	18	2.31
LSO	17	2.19	ZWE	18	2.31
			Total	**778**	**100**

A.4. Cross-correlations (1/2)

	% pop using Internet	% HH with fixed Internet	Ln # mobile subscript	Cell repaid connect charge	Fixed line faults	Ln telecom invest	# SMCs	# IXPs	# SMC owners	# years since 1st SMC	Seaquake freq 1000km rad.
% pop using Internet	1										
% HH with fixed Internet	0.8409*	1									
Ln # mobile subscript	0.7163*	0.6520*	1								
Cell repaid connect charge	-0.2746*	-0.1950*	-0.4604*	1							
Fixed line faults	-0.3970*	-0.1955	-0.5429*	0.2543*	1						
Ln telecom invest	0.3287*	0.3254*	0.3927*	-0.1839	-0.3058*	1					
# SMCs	0.5194*	0.4533*	0.4506*	-0.0831	-0.4043*	0.4208*	1				
# IXPs	0.4445*	0.3406*	0.3461*	-0.2807*	-0.1971*	0.4539*	0.4562*	1			
# SMC owners	0.4500*	0.3445*	0.4514*	-0.0521	-0.4160*	0.3589*	0.9341*	0.4028*	1		
# years since 1st SMC	0.3977*	0.3733*	0.4295*	-0.1075	-0.3958*	0.3333*	0.6370*	0.2763*	0.6614*	1	
Seaquake freq 1000km	0.0279	0.1624*	0.0014	0.0399	0.0541	-0.11	0.1198*	-0.0266	0.1084*	0.0397	1
Seaquake freq 500km	-0.0252	-0.0125	-0.0388	0.1254	-0.0043	-0.1605*	0.1194*	-0.0348	0.1050*	0.0761	0.7874*
Seaquake freq 100km	0.0019	-0.0108	-0.0058	0.1116	0.0595	-0.1168*	0.1407*	-0.019	0.1240*	0.1150*	0.4669*
SMC outages	0.0769	-0.0337	0.1361*	-0.0856	-0.1506*	0.1328*	0.1409*	0.1063*	0.1131*	0.1063*	-0.0045
Ln geo distance	-0.4575*	-0.4675*	-0.4752*	-0.0177	0.3649*	-0.1129	-0.4574*	-0.0588	-0.4707*	-0.4579*	-0.2041*
Ln capital distance	-0.3503*	-0.2544*	-0.4481*	-0.006	0.4530*	-0.067	-0.5913*	-0.0781	-0.6740*	-0.5579*	-0.1503*
Ln demographic distance	-0.4521*	-0.4219*	-0.4804*	-0.0331	0.3765*	-0.0998	-0.5182*	-0.0601	-0.5449*	-0.5126*	-0.2056*
Ln GDP/cap	0.4540*	0.5233*	0.4591*	-0.0876	-0.1601*	0.1775*	0.2402*	0.1798*	0.2717*	0.1129*	0.0436
% of 15-24yrs	0.5783*	0.6465*	0.5112*	-0.026	-0.2349*	0.1668*	0.2837*	0.2392*	0.2837*	0.1447*	0.1417*
% urban pop	0.2861*	0.2039*	0.3779*	-0.0006	-0.1265	0.0041	0.3832*	0.0588	0.4515*	0.1526*	0.1217*
Democracy status	-0.2165*	-0.1946*	-0.1658*	0.0365	0.1453*	0.008	-0.1141*	-0.1451*	-0.1613*	-0.1500*	0.0545
2^{ary} Education index	0.5811*	0.5635*	0.5648*	-0.1311	-0.3003*	0.2720*	0.3152*	0.3442*	0.3289*	0.1910*	-0.0107
Electricity access (%)	0.5028*	0.5082*	0.4637*	0.0539	-0.2130*	0.1621*	0.3504*	0.1612*	0.4038*	0.2419*	0.0892*
Landlockedness	-0.1265*	-0.1615*	-0.1176*	-0.1182	0.0779	-0.1262*	-0.3166*	0.0227	-0.3389*	0.1167*	-0.1792*
Area, in km2	0.1105*	0.2520*	0.0265	-0.0606	0.0004	0.4048*	0.1414*	0.1849*	0.0375	0.0646	-0.0904

A.4. Cross-correlations (2/2)

	Seaquake freq 500km	Seaquake freq 100km	SMC outages	Ln geo distance	Capital distance	Demographic distance	GDP/cap	% of 15-24yrs	% urban pop	Democracy status	2^{ary} Educ index	Electricity access (%)	Landlock
Seaquake freq 500km	1												
Seaquake freq 100km	0.6271*	1											
SMC outages	-0.0017	0.0111	1										
Ln geo distance	-0.1007*	-0.0943*	-0.0481	1									
Ln capital distance	-0.1207*	-0.0848	-0.062	0.7519*	1								
Ln demographic dist.	-0.1228*	-0.1254*	-0.0562	0.9816*	0.8041*	1							
Ln GDP/cap	0.0197	0.0136	-0.0558	-0.2483*	-0.2815*	-0.2616*	1						
% of 15-24yrs	0.0053	0.0818	-0.0294	-0.4275*	-0.2974*	-0.4256*	0.6738*	1					
% urban pop	0.0899*	0.1190*	-0.0262	-0.2964*	-0.4589*	-0.3753*	0.6125*	0.4545*	1				
Democracy status	0.1017*	0.0427	-0.0417	0.0503	0.1541*	0.0697	-0.2056*	-0.3592*	-0.1848*	1			
2^{ary} Education index	-0.0761	-0.0078	0.0101	-0.3489*	-0.2900*	-0.3379*	0.6992*	0.7860*	0.4788*	-0.4298*	1		
Electricity access (%)	0.0348	0.0348	-0.0321	-0.5109*	-0.4719*	-0.5235*	0.7814*	0.7163*	0.6426*	-0.2729*	0.6976*	1	
Landlockedness	-0.0873*	-0.0355	-0.0082	0.3190*	0.3849*	0.3337*	-0.2161*	-0.2859*	-0.4778*	0.0406	-0.2327*	-0.4841*	1
Area, in km2	-0.0247	-0.0471	0.0105	0.1950*	0.1086*	0.1751*	0.0778	-0.0713	-0.0506	-0.0018	-0.017	-0.0735	-0.041

B. ICT infrastructure data collection and treatment

B.1. Infrastructure deployment variables

Raw data on SMCs are drawn from Telegeography:

- All cables with date of commissioning
- All the landing stations of cables and their GPS coordinates
- The number and identity of telecoms operator-owners of cables

Raw data on Internet Exchange Points are drawn from Telegeography and completed by the *Packet Clearing House* and *Peering DB* databases:

- All IXPs with their status (active/inactive/project)
- their year of activation
- their GPS coordinates

After a conversion into polygons (disk with 5km diameter) to avoid topological inaccuracies, the SMC landing points and IXPs from each country are identified, located, and counted. Then, for each country, all cables related to these points and all IXPs are identified, which gives **the number of cables** and **the number of IXPs** variables.

The number of year since the first cable arrival is obtained by calculating the difference between the current year and the year of the first SMC's activation for each country. This variable is forward-looking and can take negative values at time t when the activation year occurs at time t + k.

Using information from Telegeography on SMC ownership structure, **the number of cable owners** is calculated for each country by summing the number of cable owners associated with all SMCs laid in that country.

B.2. digital isolation proxies

Statistical inputs: SMC landing station coordinates, countries' centroids, spatial distribution of the population.

a. Country with cables: From the SMC landing points of a given country, the distance to each point of its territory is calculated in the form of a raster map with the Spatial Analyst's Cost Distance tool, using the Winkel III projection. The Zonal Statistics tool then gives us the distance from centroid of the country to the closest SMC landing station.

b. Country without cables: From the closest foreign SMC landing points, the distance to each terrestrial point of the world is calculated as previously.

B.3. Exposure to seaquake-induced cable faults

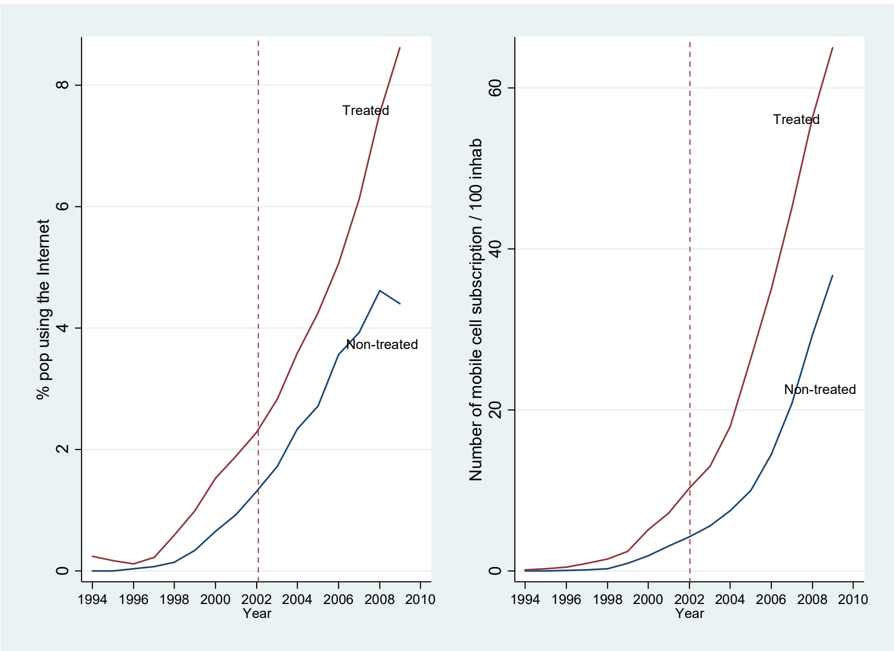
The Northern California Earthquake Data Center of the University of California, Berkeley, provides a global database of earthquakes. For each country, we get for each year the number, the location, and the average magnitude of epicentres of occurring seaquakes and are therefore able to compute the annual frequency of seaquakes within 1000-500-100 km radiuses of the stations. To ensure that we do take into account seaquakes that are strong enough to induce cable faults, we only count seaquakes with magnitudes exceeding 5 on the Richter scale. Therefore, seaquakes considered for the empirical analysis are those occurring within a 1000km radius from SMC landing stations, whose magnitudes are between 5 and 6.5 on the Richter scale.

B.4. SMC outage web-based event study

Cause	SMC	year	Countries or region affected	Fault duration
Ship	EASSy	2017	Somalia	3 weeks
Ship	WACS	2017	Congo rep	15 days
Plate tectonic	MainOne	2017	West Africa, Cameroun	14 days
Unknown	SEACOM	2016	East & South Africa	.
Sabotage	SAT-3	2015	Gabon	4 days
Sabotage	SAT-3	2015	Gabon	2-3 days
Unknown	SAT 3	2015	Nigeria	-
Sabotage	unknown	2012	Nigeria	-
Ship	TEAMS et EASSY	2012	Kenya, Burundi, Rwanda & Tanzania	15 days
Ship	SAT-3	2011	Benin, Niger, Togo, Nigeria and Burkina-Faso	10-15 days
Repeater failure	SEACOM	2010	East Africa, Europe (France & GB), India	8 days
Unknown	SAT-3	2010	Benin, Niger, Togo & Nigeria	3 weeks
Unknown	SEA-ME-WE 3, SEA-ME-WE 4 & FLAG FEA	2008	Saudi Arabaia, Djibouti, Egypt, UAE, India, Lebanon, Malaisia,Pakistan, Qatar, Syria, Taïwan, Yemen, Zambia, Malta & Italy	12 days

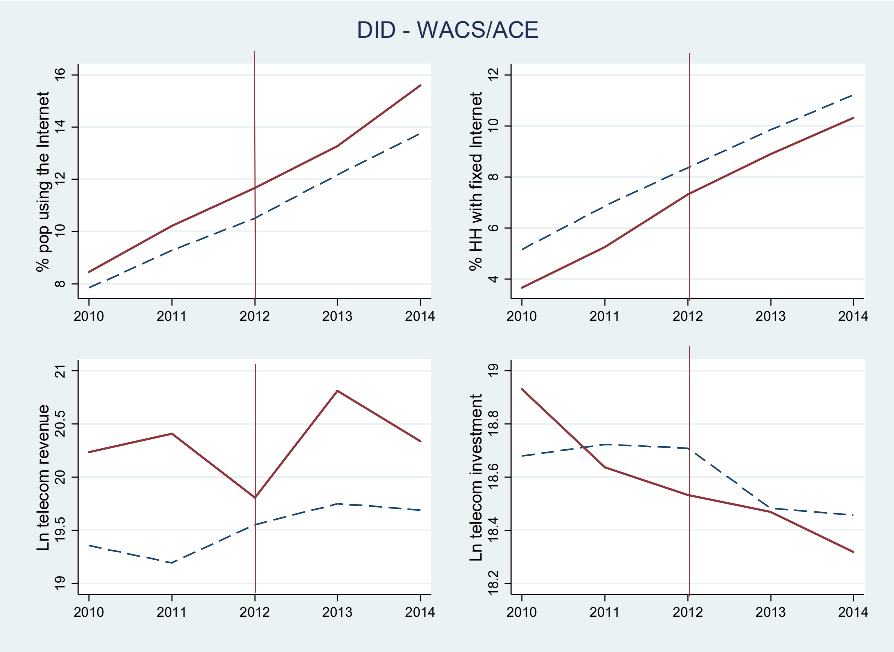
C. Diff-in-Diff analysis: other regional waves of SMCs

C.1. SAT3/SAFE (2002)



Note : because of missing data, the evolution of other ICT variable in treated and non-treated groups is not reported.

C.2. WACS/ACE (2012)



Note : because of missing data, the evolution of the share of households with fixed Internet connection variable and of the fixed phone line faults variable in treated and non-treated groups is not reported.

Tableau 2.3. Environnement concurrentiel en Afrique, par service internet, 2012-2015 (nombre de pays par catégories de concurrence).

	Haut-débit sans fil fixe			Télécommunications mobiles internationales (3G, 4G, etc.)		
	2012	2015	Δ	2012	2015	Δ
M	9	9	**0**	2	2	**0**
CP	6	3	**-3**	6	7	**1**
CE	16	20	**4**	19	20	**1**
N/A	1	1	**0**	4	5	**1**
	Passerelles Internationales a			**Communications fixes internationales longue distance**		
	2012	2015	Δ	2012	2015	Δ
M	7	7	**0**	15	19	**4**
CP	10	10	**0**	6	5	**-1**
CE	21	16	**-5**	17	14	**-3**
N/A	1	2	**1**	2	3	**1**
	Services internet			**Téléphonie mobile**		
	2012	2015	Δ	2012	2015	Δ
M	3	3	**0**	2	3	**1**
CP	5	3	**-2**	12	11	**-1**
CE	35	35	**0**	27	25	**-2**
N/A	0	0	**0**	0	0	**0**

Source: ITU Telecommunication/ICT Regulatory Database. M : Monopole ; CP : Concurrence Partielle ; CE : Concurrence Entière ; N/A : Non Applicable. L'UIT définit une passerelle internationale comme toute installation permettant d'envoyer des communications électroniques (voix, données et vidéo) entre les réseaux nationaux d'un pays et un autre. En pratique, les passerelles fournissent des liaisons soit par un système de câble international (souvent sous-marin), soit par un satellite via une station terrienne. Les nombres sont le nombre de pays africains placés en catégories M, CP, CE, N/A