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Telecommunication Submarine-Cable Deployment and the Digital Divide in Sub-Saharan Africa*

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Abstract

This paper estimates the impact of fiber-optic submarine cables (SMCs) deployment on the digital divide in 46 sub-Saharan African (SSA) countries. It shows that the laying of SEACOM, MainOne and EASSy cables has yielded a 3-4% point increase in internet penetration rates. Moreover, it also shows that the reduction in landlocked countries' digital isolation, following the laying of SMCs, has boosted Internet access and reduced telecommunication disruptions. Finally, it stresses that the arrival of SMCs may increase countries' vulnerability to SMC faults, by showing how SMCs exposure to seismic risk lowers Internet and mobile penetration rates, and increases telecommunication disruptions.

Keywords: ICT, Internet, submarine cables, seismic risk, digital divide, Sub-Saharan Africa, infrastructures.

JEL Classification: 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 that play an increasing role in the development process. By contributing to the emergence and dissemination of innovations in trade, agriculture, financial services and transportation, and to the modernization of public administrations, the digitization of the economy has 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 subcontinent, 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 (Schumann & Kende, 2013; Buys et al, 2009; Bates, 2014) and the poor governance of the telecommunication sector (Howard & Mazaheri, 2009; 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 the rich, the urban and the most educated (World Bank, 2016).

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

During the last decade, global connectivity has improved significantly with the worldwide deployment of more than 400 fiber submarine cables (SMCs) over the period 1990–2018, transmitting more than 99% of international telecommunications. However, SSA has remained relatively digitally isolated until 2009. Since then, the digital infrastructure has 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.

SMCs are hence vital infrastructures for the economy, and their recent laying in SSA has also increased the subcontinent's vulnerability to SMC failures. As an illustration, on 10th 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 deprived Internet users in Benin, Togo, Niger, Burkina Faso and Nigeria for 10 to 15 days. More recently, in June 2017, the Main-1 cable broke 3000 km to the south of Portugal, disturbing the Internet in several countries in West Africa. In the same month, the anchor of a container ship accidentally cut the only 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 be more than 10 million dollars a day.

This paper brings new insights into the digital divide determinants in SSA by analyzing the contribution of the maritime infrastructure deployment to ICT outcomes in the subcontinent. This empirical analysis is conducted in three steps. First, this paper provides novel evidence on the impact of 2009-2010 regional waves of SMCs on Internet access, using a Difference-in-differences (DID) approach. According to DID estimates, the deployment of SMCs in SSA has yielded a 3-4 percentage point increase in Internet penetration rates, corresponding to almost a doubling of Internet penetration in the subcontinent. Second, it emphasizes that this deployment has reduced digital isolation of landlocked countries, by increasing Internet penetration and lowering landline phone-line faults. Third, it highlights that the deployment of SMCs has come with an increasing vulnerability to SMC faults, by stressing how seismic risk in the neighborhood of SMCs lowers Internet and mobile penetration rates, and increase the telecommunication network instability.

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 in SSA (Ndulu, 2006; Buys et al, 2009). First, this paper exploits a novel database on various features of SSA's SMC network to analyze the development of ICTs in the subcontinent. Second, the paper quantifies the macro-level impact of SMC-laying on Internet access through a DID framework. Third, this paper highlights both the benefits and the risks incurred by SMC deployment, by providing evidence on the positive impact of SMC arrival in SSA, and the negative impact of related vulnerabilities, on ICT outcomes.

The next section presents a DID analysis of the effect of SMC deployment on Internet penetration rates in a sample of 46 SSA. The third section focuses on the effect of SMC arrivals on landlocked countries' international digital isolation. The fourth section addresses the question of the African cable network exposure to seismic risk and its impact on ICT outcomes. The fifth section concludes.

2. SMC deployment and the digital divide 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 subcontinent.

2.1. The maritime telecommunication infrastructure deployment in sub-Saharan Africa

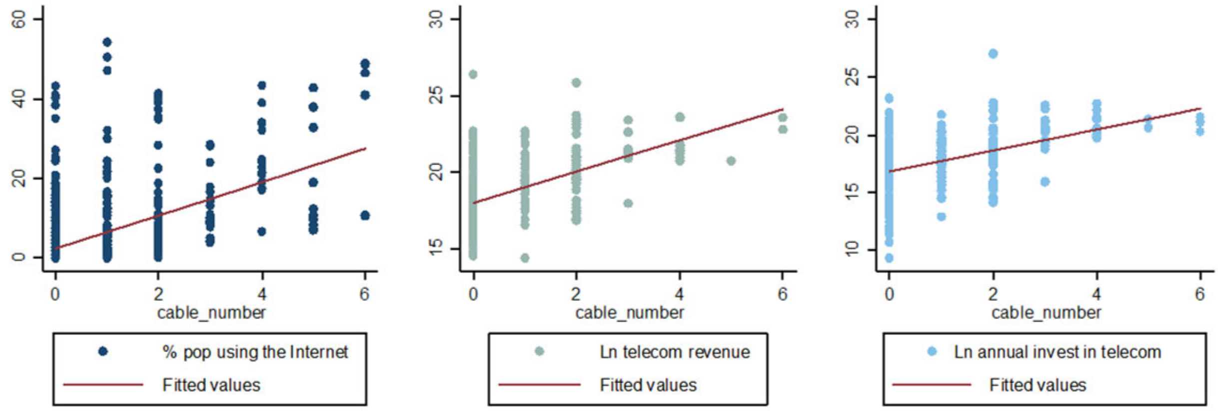
In 2015, SSA was connected to the world Internet through 15 SMCs, nine being spread over its west coast, and six over its east coast.[1] The laying of these cables has accelerated the development of the digital economy through greater access to affordable and fast Internet and mobile technologies, thereby improving the performance of firms (Cariolle et al, 2019; Paunov & Rollo, 2015, 2016), facilitating job creation (Hjort & Poulsen, 2017), increasing trade flows and foreign direct investments (Freund & Weinhold, 2004), and enhancing the quality of governance (Andersen et al, 2011; Asongu & Nwachukwu, 2016). The potential benefits of the deployment of such infrastructures are therefore very important (Röller & Waverman, 2001; Czernich et al, 2011).

The global network of submarine fiber-optic wires represents the first link in the Internet access chain, and the most efficient option for delivering international telecommunications services (e-mail, phone calls, video content, etc.). In the absence of SMC, a country has two solutions for obtaining an international Internet connection: i) buying expensive and limited Internet bandwidth to a neighboring country hosting a SMC (which necessitates being connected to that country by a terrestrial wireline infrastructure), or ii) buying Internet bandwidth – which is costly, slow and limited – to communication satellites.

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 & Woodcock, 2013; Schumann & Kende, 2013; Telegeography, 2016). To illustrate the interplay between the deployment of SMCs and some telecommunication outcomes in SSA, the graphical correlation between the number of SMCs and three common metrics of the telecom sector development is reported in Figure 1. This graph demonstrates a positive correlation of SMC deployment with Internet penetration rates, and with the revenues and investments of the telecom sector.

[1] **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) and 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) and DARE (60 terabits) are expected in 2018.

Figure 1. SMC deployment and the telecom sector, sub-Saharan Africa, 1990–2014.



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

2.2. Diff-in-Diff (DID) analysis

Using a panel dataset covering about 46 African countries over the period 1990–2014, this empirical subsection tries to unravel the contribution of the submarine telecom infrastructure to ICTs, by studying the impact of the deployment of SMCs on Internet access within DID framework.

2.2.1. DID framework

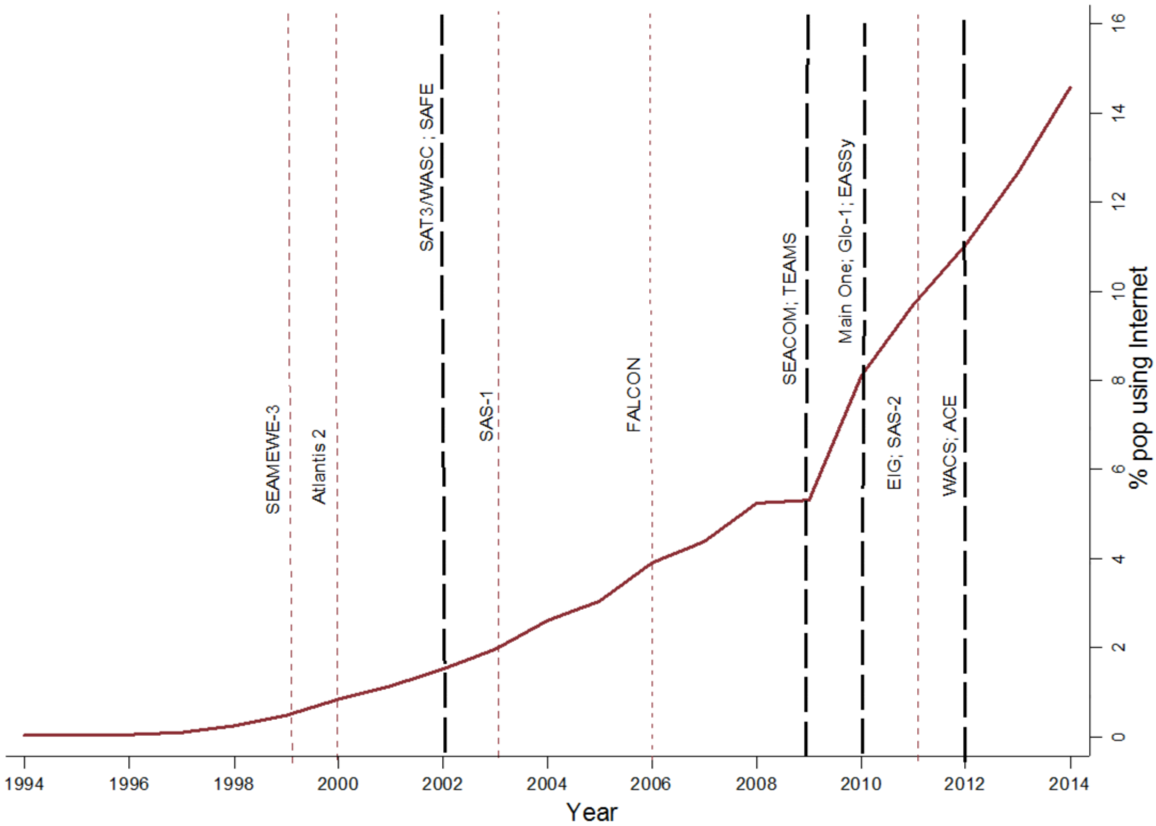
A DID estimation framework (Card & Krueger, 1994; Heckman et al, 1998) is adopted to study the impact of different waves of SMC arrivals on final telecommunication outcome variables. Among the different waves of SMCs that connected SSA to the global Internet, only SMCs deployed regionally, i.e. SMCs connecting at least four sub-Saharan African countries together or to another continent, were considered. In fact, SMCs are often deployed regionally because of the small market-size of many SSA countries, and because of the high fixed-cost of this infrastructure, requiring public and private telecom operators and investors from various neighboring countries to share them (Jensen, 2006). By contrast, the laying of SMCs connecting a smaller number of countries could be influenced by national policy-related factors rather than aggregate regional considerations, and therefore make the treatment endogenous. Among the various waves of regional SMC arrivals in SSA (see Figure 2), the following regional cables are considered:

1. The SAT3, WASC, SAFE cables deployed in 2002, connecting South Africa, Angola, Gabon, Cameroon, Nigeria, Benin, Ghana, Ivory Coast, Senegal and Mauritius to Asia and Europe.
2. The SEACOM cable deployed in 2009, connecting South Africa, Tanzania, Kenya and Djibouti to Asia and the Middle-East.
3. The MainOne and EASSy cables deployed in 2010, respectively connecting the Senegal, Ivory Coast, Ghana and Nigeria to Europe, and South Africa, Madagascar, Comoros, Tanzania, Kenya, Somalia, Djibouti and Sudan together.

4. The WACS and ACE cables deployed in 2012, connecting South Africa, Namibia, Angola, the RDC, the Congo, Cameroon, Nigeria, Togo, Ghana, Sierra Leone, Ivory Coast, Cap Verde, Liberia, Benin, Guinea, Gambia, and Mauritania to Europe.

The figure 2 below shows how the average Internet penetration rate has been increasing with the successive arrival of SMCs in the subcontinent. In particular, there is a striking regime shift in Internet penetration evolution after the arrival of 2009 and 2010 regional SMCs deployment (waves 2 and 3).

Figure 2. SMC arrivals and Internet penetration in SSA.



Source: author. Long dashed vertical lines: arrival of a transcontinental regional SMC, connecting at least four African countries. Short dashed vertical lines: arrival of a transcontinental local SMC, connecting less than four African countries.

Once the treatment is identified, i.e. the relevant SMC wave, the following equation is estimated:

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

Where *j* indexes the treated and untreated groups, with j=1 for the treatment group (country *i* has been connected to the global Internet by an SMC at time *t*) and j=0 for the control group (country *i* has not been connected to the Internet by an SMC at time *t*). Telecommunication outcomes, ICT_{it}, are the Internet penetration rate in the population, that is, the share of Internet users in the population, or by the mobile penetration rate, that is, the number of mobile cellular subscriptions per 100 inhabitants.[2] D_t^j is a dichotomous variable equal to one when country is treated and zero otherwise. $X_{i,t}$ is a vector of control variables, while d_i and d_t are country and time dummies, respectively controlling for unobserved time-invariant country characteristics and country-invariant time characteristics. Therefore, the country fixed-effects d_i controls for the time-invariant difference in Internet penetration rates between the treatment and control groups, while the time fixed effect d_t captures how both groups are affected over time by the SMC arrival. Assuming that the error term $\varepsilon_{i,t}^j$ is independent from the treatment, i.e. $E(\varepsilon_{i,t}^j | D_t^j) = 0$, the parameter δ_1 is the coefficient identifying the causal effect of the treatment – the SMC arrival – on telecom outcomes. This causal effect is hence 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.

Control variables X_{it} included 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 with access to electricity[3], and the number of Internet exchange points to proxy the terrestrial infrastructure deployment[4].

2.2.2. SMC regional arrivals and the parallel trend assumption

One critical assumption of the DID estimator is the parallel trend assumption, which requires outcome variables to follow parallel trends in the absence of treatment, in our case, SMC arrivals. Without information on what would have happened without treatment, one common practice is to check the existence of a parallel trend before the treatment. To do this, Figure 3 plots the co-evolution of these outcomes for treatment and control groups related to waves 2 and 3 taken together, between 2002 (after wave 1) and 2012 (before wave 4). These two waves are indeed associated with a marked change in Internet penetration growth rates, as shown in figure 2. A visual inspection of this graph supports that these two waves of SMC deployment are a relevant experiment for a DID analysis, as i) Internet penetration rates of treated and non-treated groups exhibit parallel but also same-level pre-treatment trends, and ii) these trends greatly diverge after the treatment.

By contrast, these waves of SMCs do not seem to have impacted on the penetration of mobile phones, suggesting that mobile phone adoption in SSA is not related to fast Internet arrival

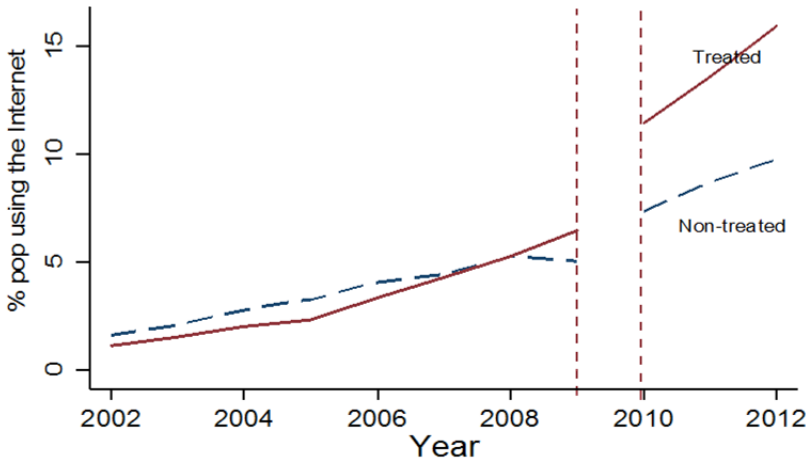
[2] The Internet penetration rate in the population is used as the main final outcome variable because it better reflects Internet usage in Africa (access to the Internet via Internet cafés and through mobile phones) than the share of households with an Internet subscription, which depends on the wireline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

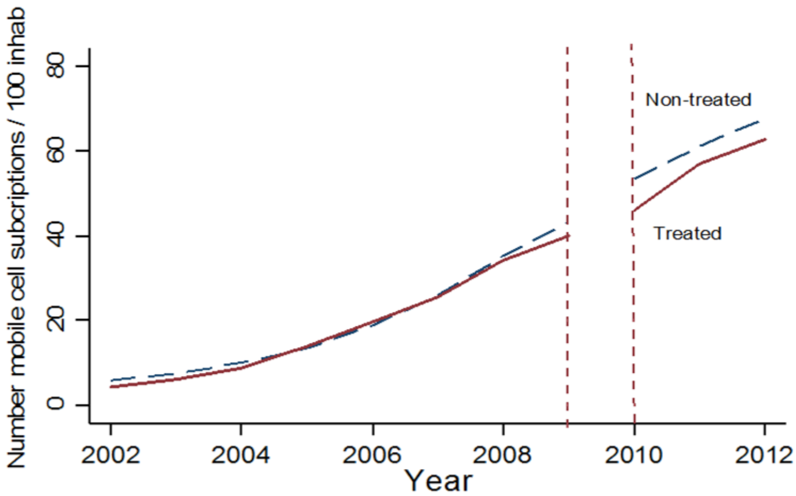
[3] As this last variable is documented sporadically, missing data are replaced by five-year moving averages. When a five-year average cannot be calculated, we use the previous five-year average value.

[4] Internet exchange points are physical Internet hubs that permit the reduction of communication latency, by promoting direct interconnections between countries, and the saving of 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 IXP network is a central element for the development of local and regional Internet ecosystems (Malecki, 2002; Weller & Woodcock, 2013; OECD, 2014).

because it has leapfrogged the lack of landline telecommunication infrastructures (Aker & Mbiti, 2010). It is worth mentioning that the parallel trend assumption seems to hold when considering wave 2 alone as the treatment (see Appendix D.2). However, SEACOM (wave 2) and the MainOne/EASSy's (wave 3) deployment are considered as one single treatment, as they occurred from one year to another and may have a confounding effect on ICT outcomes' evolution. Therefore, the following DID analysis will therefore focus on the impact of waves 2 and 3 taken together on Internet penetration rates.[5]

Figure 3. Trend comparison of telecom outcomes between treatment and control groups.





Source: author. Raw data from ITU (2016).

[5] The co-evolutions of these outcomes related to waves 1, 2 and 4 are reported in Appendix B but are not considered in the following analysis because waves 1 and 4 seem to have had little influence on telecommunication outcomes.

2.2.3. Baseline results

DID Estimations of eq. (1) are run over various samples:

- Sample A1: using an original sample of 46 SSA countries over the 2002-2012 period.
- Sample A2: excluding Djibouti and Sudan from this sample to neutralize the eventual effect of the SAS1&2-EIG-FALCON cables, deployed in these two countries between 2002 and 2012, on SSA Internet penetration rates (see Figure 2).
- Sample A3: over 1990-2014, to check the sensitivity of estimates to an extended estimation period, marked by other national and regional SMCs laying.

Estimates are reported in table 1 and support that the SEACOM/EASSy/MainOne cables had a strong, positive and significant impact on Internet penetration rates.[6] First, results from the original sample A1 show that these waves led to an approximate 4 percentage point increase in the share of the population using the Internet. Estimates lie within the same range and remain 1% significant when excluding Djibouti and Sudan from the sample (sample A.2) – countries where national SMCs have landed between 2002 and 2012 – and when the estimation period is extended to 1990-2014 (sample A.3). These baseline results support that the arrival of 2009-2010 SMCs has almost doubled the penetration of Internet in the subcontinent (see pre-treatment Internet penetration rate in figure 2). They also suggest that the impact of other SMC-laying is limited, as estimates are little affected by the extension of the estimation period and by the exclusion of SMCs single-recipient countries.

Table 1. DID baseline estimations

Dep Var.: % population using the Internet	**DID parameters (δ_1)**	**# observations**	**# treated/control obs**	**R-squared**
Sample A1: 46 SSA countries, 2002-2012.	4.136*** (4.94)	405	97/308	0.87
Sample A2: SSA excl. DJI and SDN, 2002-2012.	4.491*** (4.89)	389	81/308	0.87
Sample A3: 1990-2014	4.409*** (5.79)	798	196/602	0.76
Controls	Ln GDP/cap, % 15- to 64-yrs-old pop, % of urban pop, % pop with electricity access, 2ndary educ index, democracy, IXP number			
Time & country fixed effects	YES			

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

[6] DID estimations considering the mere SEACOM deployment in 2009 as treatment, are reported in Appendix D. The resulting estimates are very close to those reported in table 3.

2.2.4. Sample restrictions and the endogeneity concern

However, the focuses placed on regional SMCs, combined with the marginal constraints placed on the sample composition, are not sufficient restrictions to ensure that estimates do not suffer from estimation biases. Because regional SMCs may have landed in specific countries for non-exogenous reasons, additional and more substantial sample restrictions are made to address an eventual estimation bias. A first way to address this bias is to exclude from the sample all coastal African countries that have been, for some geopolitical or policy-related unobserved matters, the single recipient of a transcontinental SMC. This restriction leads to the exclusion of Djibouti, Senegal, Sudan, and Kenya from the sample (sample B).

A second source of endogeneity is the emerging nature of some African telecom markets which may influence telco operators' decision to deploy their SMC in specific countries rather than others. To address this possibility, emerging markets for telecommunications are identified as (coastal) countries with fast and medium-growing middle class identified in Deloitte (2014), and are excluded accordingly (sample C). Excluded telecom markets are Cap Verde, Gabon, Ghana, Ivory Coast, Kenya, Liberia, Mauritania, Nigeria, Senegal, South Africa, Namibia, Angola, and Eritrea. Mauritius is also excluded from sample C because its low tax system combined with its favorable geographic position may make it particularly attractive for telecom infrastructure investments.

Third, since the non-laying of a regional SMC in a country may also be explained by the bad quality of national policies and regulations, coastal countries located on regional SMCs' path but not connected to them are excluded for this concern. Proceeding to this restriction, the sample excludes Benin, Comoros, Eritrea, Gambia, Guinea, Guinea-Bissau, Liberia, Mauritania, Madagascar, Sierra Leone, Somalia, and Togo (Sample D).

Fourth, landlocked countries are also excluded because they cannot directly host SMCs (Sample E). This geographic feature makes them particularly dependent on their neighboring coastal countries receiving SMCs, so that the non-treatment might act in a different way these countries compared to their coastal counterpart.

Results are reported in Table 2. They support a robust, consistent, positive and 1%-significant effect of SMC deployment on Internet usage. Estimates suggest that the arrival of SMC in 2009-2010 has increased by around 3-4 points the penetration of Internet in the sub-continent. Interestingly, the impact of SMC laying on coastal countries, that is, excluding landlocked countries from the sample (sample E), lies around 3 percentage point increase, which is lower than estimates obtained using samples including landlocked countries. This suggests that, even though landlocked countries are not directly connected to the International telecom infrastructures, they may have been positively impacted by SMC deployment. This issue is therefore furthered the next section.

Table 2. DID estimations, sample restrictions

Dep Var.: % population using the Internet	DID parameters (δ_1)	# observations	# treated/control obs	R-squared
		Waves 2 & 3		
Sample B: SSA excl countries being exclusive cable host.	2.993*** (3.13)	371	63/308	0.89
Sample C: SSA excl. dynamic coastal telecom markets.	3.658*** (3.83)	294	52/242	0.89
Sample D: SSA excl. unserved coastal countries	3.752*** (4.08)	344	97/247	0.87
Sample E: SSA coastal countries (excl. landlocked countries)	2.947*** (2.95)	280	97/183	0.89
Controls	Ln GDP/cap, % 15- to 64-yrs-old pop, % of urban pop, % pop with electricity access, 2ndary educ index, democracy, IXP number			
Time & country fixed effects	YES			

t-student in parenthesis. $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors robust to heteroscedasticity. Sample B: countries excluded from the sample are Djibouti, Senegal, Sudan and Kenya. Sample C: countries excluded from the sample are Cap Verde, Gabon, Ghana, Ivory Coast, Kenya, Liberia, Mauritius, Mauritania, Nigeria, Senegal, South Africa, Namibia, Angola, and Eritrea. Sample D: countries excluded from the sample are: Benin, Comoros, Eritrea, Gambia, Guinea, Guinea-Bissau, Liberia, Mauritania, Madagascar, Sierra Leone, Somalia, and Togo.

3. SMC deployment and the spatial digital divide: evidence from landlocked African countries

Inland infrastructure deployment is one of the major challenges for the telecom industry and the whole economy in low-income countries, especially SSA countries (Ndulu, 2006; Towela & Tesfaye, 2015; Bates, 2014; Weller & Woodcock, 2013). That is why landlocked African countries face considerable handicap to bring a stable, fast and affordable Internet to the population. Despite this structural handicap, previous results tend to support that the laying of regional SMCs along African coasts has had a positive effect on Internet penetration in landlocked countries. Such evidence would be explained by the narrowing continental gap between landlocked populations and international maritime infrastructures laid alongside the coast, and the increasing reliance on mobile network rather than fiber Internet infrastructure terrestrial network in the region. By studying the effect of the decreasing distance to SMC landing stations on telecommunication outcomes in landlocked countries, this section highlights the importance of the spatial digital divide in these countries, and indirectly addresses the possible endogeneity bias in the timing and location of SMC deployment.

3.1. Digital isolation and ICT outcomes: why distance to infrastructure matters

Various studies have stressed how locations distant from key infrastructures experience lower access to telecommunications, and are more exposed to telecommunication disruptions[7] (Buys et al, 2009; Ndulu, 2006; Gorman & Malecki, 2000; Gorman et al., 2004; Malecki, 2002). As a result, the geography of SSA landlocked countries – characterized by vast territories, a large rural population, and infrastructures concentrated in capital cities – reduces the digital dividends of SMC deployment over the subcontinent.

Digital isolation in some areas therefore depends on both structural factors, such as the territorial fragmentation of the continent, landlockedness, the size of the country, the altitude and 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 (Buys et al., 2009; Jensen, 2006; Sutherland, 2014). The study of the geographic determinants of digital isolation, by their exogenous nature, is of particular interest here. For this purpose, three distance variables have been computed to proxy digital isolation:

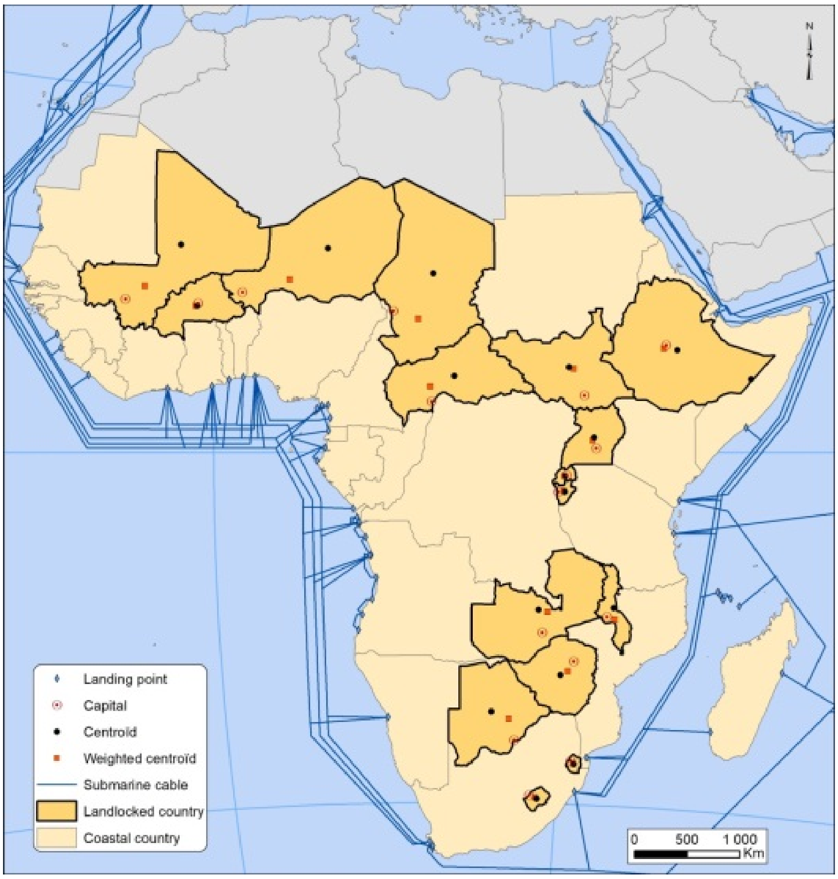
- The **geographic centroid distance to SMC**, i.e. the distance between the geographic centroid and the closest SMC landing station. This geographic distance is the bird's-eye distance required for the deployment of the backbone telecom infrastructure that minimizes the infrastructure gap for any random locations in the territory.
- The **capital distance to SMC**, 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 to SMC**, 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 both the geographic distance and the capital distance previously mentioned.

In other words, the geographical distance to SMCs reflects the geographical handicaps faced by large and/or landlocked countries in bringing ICTs over the whole territory. The capital and demographic distances both reflect the geographical handicap faced by large, landlocked and rural countries in bringing ICTs to their population. Figure 4 below gives an idea of these distances

[7] Grubesic and Murray (2006) show that in the US, where telecommunication assets are geographically concentrated – which is also the case in SSA – telecommunication network cascading failures are more likely to occur, and to affect locations distant from vital infrastructures nodes. 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 shutdowns.

in SSA landlocked countries by mapping these countries' centroid, weighted centroid, capitals and coastal SMC landing stations.

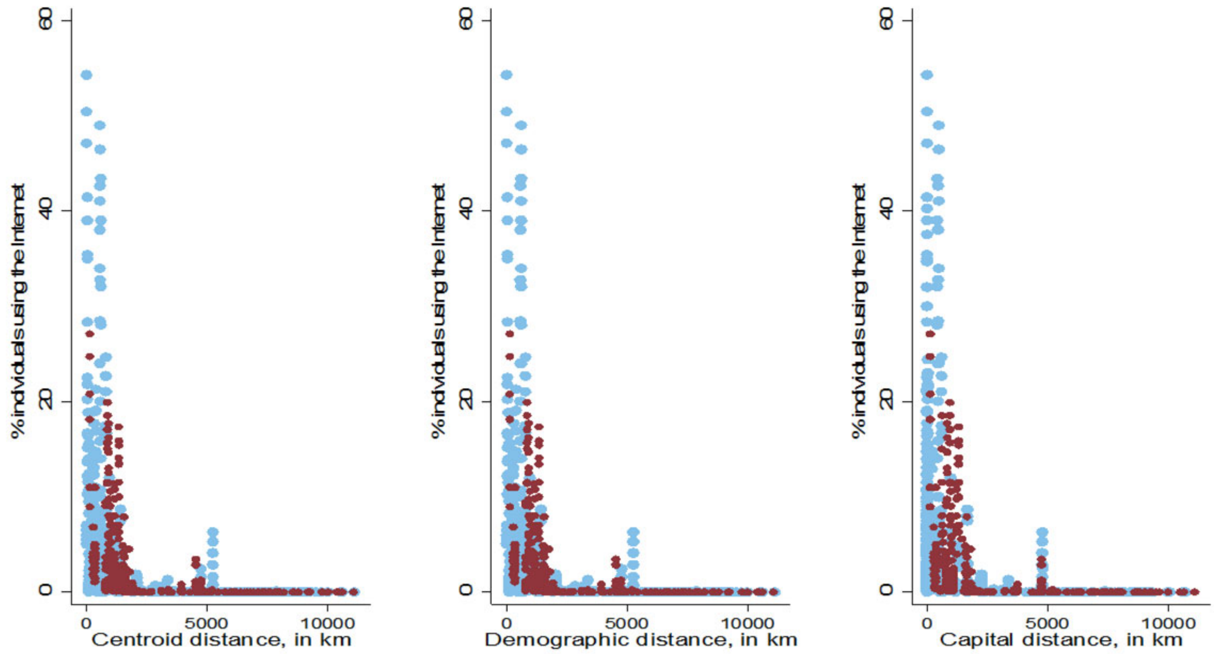
Figure 4. Capitals, geographic and demographic (weighted) centroids and SMC landing stations in sub-Saharan Africa in 2015.



Source: author.

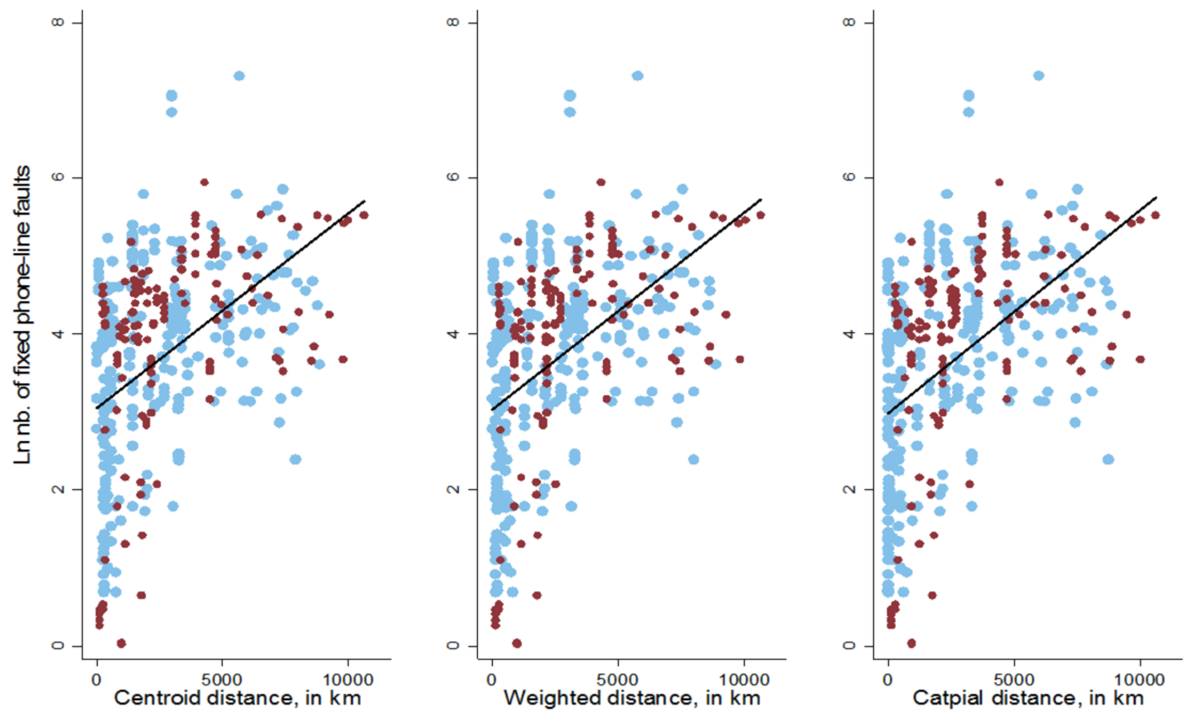
The longer these distances to SMC landing stations, the more likely its digital isolation, the lower its access to Internet, the higher its exposure to telecommunication disruption. To illustrate this relationship, figures 5 and 6 present the graphical correlation of these three distance variables with Internet penetration rates and the number of fixed phone line faults, respectively. They highlight a negative correlation between digital isolation and Internet access on the one hand (figure 5), and a positive correlation between digital isolation and the telecommunication network instability on the other hand (figure 6). These relationships appear to hold for landlocked countries, plotted in red in the graphs. In the next section, I proceed to an econometric analysis to study whether the progressive laying of SMCs along Africa's coasts has reduced digital isolation in landlocked countries, and thereby, has positively impacted their telecommunication sector.

Figure 5. Graphical correlation between distances to SMC and Internet penetration in SSA, 1990-2014.



Source: author. Data: author and ITU (2016). **Notes:** SSA coastal countries are represented in light blue dots, while landlocked countries are represented in red dots.

Figure 6. Graphical correlation between distances to SMC and the landline telecom network instability in SSA, 1990-2014.



Source: author. Data: author and ITU (2016). Notes: SSA coastal countries are represented in light blue dots, while landlocked countries are represented in red dots.

3.2. Estimating the impact of SMC deployment in landlocked countries

In this second step, a multivariate econometric analysis of the impact of the reduction of countries' digital isolation, resulting from the progressive SMC deployment alongside African coasts, on the telecommunication sector is conducted on a sample of 14 landlocked countries over 1990-2014. The *within* fixed-effect estimator is applied to the following specification:

$$\mathrm{ICT}_{i,t} = \alpha_0 + \alpha_1 . \mathrm{X}_{i,t} + \alpha_2 . \mathrm{DIST}_{i,t} + \theta_i + \rho_t + \omega_{i,t} \quad (2)$$

Where $ICT_{i,t}$ is the telecommunication outcome variable in country *i* and year *t*, $X_{i,t}$ is a vector of control variables. $DIST_{i,t}$ are the three distance variables included separately, discussed previously. θ_i and ρ_t are the country and time fixed-effects, respectively controlling for unobserved fixed country and time heterogeneity, and $\omega_{i,t}$ is an error term.

3.2.1. Data

This empirical analysis covers 14 countries and the period 1990-2014. Descriptive statistics, correlations between variables are provided in Appendix A. Variables' sources and definitions are provided in Appendix D.

Telecommunication outcome variables (ICT_{it}) consist of two final outcome variables – the Internet and mobile penetration rates – and two intermediary outcome variables – the mobile cellular prepaid connection charge[8], and the annual number of fixed phone-line faults[9]. Intermediary outcome variables, by measuring telecommunication tariffs and the network instability, further the comprehension of the channels linking digital isolation to final telecommunication outcomes.

Control variables (X_{it}) 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 with access to electricity[10], and the country number of Internet exchange points to proxy the terrestrial infrastructure deployment[11].

[8] This mobile prepaid tariff variable is preferred to other tariff variables such as mobile monthly subscription charge because of better data availability, and because it better reflects mobile phone usage in SSA.

[9] However, this variable does not fully reflect the overall network instability since: i) faults that are not the responsibility of public operators are not recorded (see Appendix D), ii) it does not take into account disturbances of the cellular network, and iii) those incurred on private operator networks. It therefore partially reflects, perhaps understates, the overall network instability.

[10] As this last variable is 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.

[11] Internet exchange points are physical Internet hubs that permit the reduction of communication latency, by promoting direct interconnections between countries, and the saving of 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 IXP network is a central element for the development of local and regional Internet ecosystems (Malecki, 2002; Weller & Woodcock, 2013; OECD, 2014).

3.2.2. Results

A first round of OLS and fixed effect (FE) panel estimations excluding distance variables and taking the Internet penetration rate as outcome variable are conducted and reported in Table 3. To ensure that results are not affected by auto-correlated disturbances, FE estimations are also conducted with AR(1) error terms (but without time dummies).[12] Control estimates, when significant, have the expected sign, and digital isolation variables are negatively, significantly and consistently correlated with Internet penetration rates. Samples estimates suggest that a one-standard deviation decrease in the three distances to SMC landing station would result into an approximate 0.8 percentage point increase in Internet penetration rates in landlocked countries. Moreover, results support that all three distances have a similar impact on Internet penetration rates, so that in the next round of estimations, we focus on the geographical centroid distance variable given its strict geographical (and therefore exogenous) nature.

[12] Estimates are robust and consistent when higher order autocorrelation is assumed. They can be provided upon request.

Table 3. Infrastructure deployment and the telecom sector in SSA, *within* fixed-effect (FE) panel estimations (1/2)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Dep var: Internet penetration rate								
Ln GDP/cap	-2.095	-1.400	-1.400	-2.137	-1.455	-2.242	-1.543	-2.239	-1.544
	(-0.70)	(-0.44)	(-1.52)	(-0.82)	(-1.63)	(-0.86)	(-1.69)	(-0.83)	(-1.68)
% of 15–24yrs	0.320	0.337	0.337***	0.0904	0.145*	0.114	0.175**	0.134	0.191**
	(1.66)	-1.550	(4.71)	(0.56)	(2.00)	(0.74)	(2.58)	(0.82)	(2.88)
% urban pop	-0.160	-0.154	-0.154**	-0.112	-0.182***	-0.104	-0.181***	-0.106	-0.181***
	(-0.92)	(-0.79)	(-2.41)	(-0.82)	(-3.55)	(-0.76)	(-3.48)	(-0.77)	(-3.46)
Democracy	0.386	0.641*	0.641***	0.517	0.818***	0.487	0.791***	0.485	0.785***
	(0.94)	(2.480)	(3.09)	(1.49)	(3.78)	(1.49)	(3.67)	(1.46)	(3.65)
2^{ary} Education	-0.0140	0.068	0.0684**	0.00760	0.0821***	0.00344	0.0780***	-0.00131	0.0751***
	(-0.27)	(1.12)	(2.84)	(0.15)	(3.25)	(0.07)	(3.12)	(-0.03)	(3.02)
Electricity access (%)	0.180	0.194***	0.194***	0.0794	0.110	0.0716	0.106	0.0708	0.108
	(1.26)	(4.51)	(3.35)	(0.54)	(1.50)	(0.49)	(1.39)	(0.50)	(1.45)
# IXPs	3.413***	4.435**	4.435***	3.573***	4.403***	3.785***	4.502***	3.806***	4.511***
	(3.57)	(4.140)	(4.39)	(3.46)	(4.60)	(3.51)	(4.55)	(3.46)	(4.52)
Digital isolation:									
Ln geo distance				-1.356***	-0.939***				
				(-3.26)	(-3.70)				
Ln demo distance						-1.402***	-0.877***		
						(-3.33)	(-3.42)		
Ln capital distance								-1.384***	-0.844***
								(-3.32)	(-3.38)
Year dummies	Yes	No	No	Yes	No	Yes	No	Yes	No
Driscoll-Kraay standard errors	No	No	Yes	No	Yes	No	Yes	No	Yes
N	321	321	321	321	321	321	321	321	321
# countries	14	14	14	14	14	14	14	14	14
R^2 (within)	0.731	0.621	0.621	0.756	0.649	0.754	0.646	0.752	0.645

t-student in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors are robust to heteroscedasticity, and robust to both heteroscedasticity and first-order autocorrelation in columns (3), (5), (7) and (9).

Table 4 reports FE estimates using the three other telecom outcomes as dependent variables, namely, the mobile penetration rate, the cellular prepaid connection charge and the annual number of fixed phone-line faults. Results support that digital isolation, in addition to reducing Internet penetration rates, increases the telecommunication network instability. However, there is no significant evidence of an effect of digital isolation on mobile penetration rates or on the cellular prepaid connection charge, which may be explained by the fact that mobile phone adoption has been a response to the lack of landline telecommunication infrastructures in Africa (Aker and Mbiti, 2010).

Table 4. Infrastructure deployment and the telecom sector in SSA, within fixed-effect (FE) panel estimations (2/2)

	(1)	(2)	(3)	(4)	(5)	(6)
Dep. var	**Mobile penetration**		**Cell. prepaid charge**		**# Fixed phone-line faults**	
Ln GDP/cap	3.667	8.365**	20.60	2.978	-0.426	-0.452
	(0.50)	(2.40)	(1.39)	(1.16)	(-0.47)	(-0.63)
% of 15–24yrs	1.061	1.514**	1.142**	0.620***	-0.0154	-0.0476
	(0.86)	(2.71)	(2.70)	(6.98)	(-0.17)	(-0.69)
% urban pop	1.312	0.724	-0.0795	-0.338***	0.0965	0.127**
	(1.76)	(0.82)	(-0.88)	(-3.91)	(0.79)	(2.40)
Democracy	4.055**	6.962**	-0.739	0.739***	0.148	0.135
	(2.19)	(2.32)	(-0.77)	(3.50)	(0.84)	(0.50)
2^{ary} Education	0.0582	0.787***	0.0657	-0.151***	0.0100	-0.0228
	(0.17)	(3.51)	(0.51)	(-4.84)	(0.39)	(-1.06)
Electricity access (%)	1.440	0.957	-0.0202	0.0187***	-0.145	-0.0603
	(1.50)	(1.31)	(-0.30)	(5.16)	(-1.00)	(-1.18)
#IXPs	2.516	10.54***	-0.474	-0.836***	-0.853	-1.310**
	(0.53)	(4.34)	(-1.03)	(-3.20)	(-1.77)	(-2.90)
Digital isolation:						
Ln geo distance	-3.601	-1.046	-0.941	0.990	0.492*	0.454**
	(-1.31)	(-0.59)	(-0.84)	(1.65)	(1.92)	(2.97)
Year dummies	Yes	No	Yes	No	Yes	No
Driscoll-Kraay standard errors	No	Yes	No	Yes	No	Yes
N	322	322	64	64	144	144
# countries	14	14	14	14	13	13
R^2 (within)	0.834	0.642	0.622	0.435	0.671	0.624

t-student in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors are robust to heteroscedasticity, and robust to both heteroscedasticity and first-order autocorrelation in columns (2), (4), (6).

By studying the effect of the geographical distance to SMCs on the digital divide in landlocked countries, this empirical section has emphasized the problem of international digital isolation for these countries and its impact on the digital divide. It stresses that the distance to SMCs is a critical determinant of populations' access to Internet, but it also appears to be a factor of digital vulnerability by increasing telecom network instability. The next section furthers the issue of telecom sector vulnerability.

4. Sub-Saharan Africa's vulnerability to SMC faults

Digital vulnerability could be defined as the risk for a country and its population of access to telecommunication services being 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 external shocks and internal failures (server breakdowns, SMC outages, closing of data centers or Internet exchange points), power outages and cyber-attacks. This section focuses on digital vulnerability related to the SMC's exposure to seismic risk.[13]

4.1. Seismic activity and the safety of the SMC network

As shown previously, the recent and massive laying of fiber SMCs in SSA is a major driver of progress for the telecom sector, and probably for the digital economy's expansion as a whole. However, SMC deployment over the subcontinent has also increased its vulnerability to SMC outages, mostly resulting from two external sources (Carter et al, 2009; Clark, 2016, Yincan et al, 2018):

- 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 seismic shocks, typhoons, floods, volcanic eruptions and turbidity currents, which are the main cause of multiple simultaneous SMC breaks.

Because of their unpredictable and unavoidable nature, natural events affecting the functioning of SMC are of particularly interest for this study (Yincan et al, 2018). Among these events, seismic activity is known to be the major natural cause of cable wear or breaks, by shaking the submarine and water body violently, by provoking turbidity currents, landslides, seabed sand waves, and tsunamis (Soh et al, 2004; Carter et al, 2009; Clark, 2016; Aceto et al, 2018; Yincan et al, 2018). Compared to other sources of SMC faults, earthquakes and seaquakes may damage an entire section of the cable network (Palmer-Felgate et al, 2013; Yincan et al, 2018), and may therefore be costlier for the economy. Moreover, by dislocating the seabed strata, deforming the soil, provoking landslide, seismic activity may have persistent adverse effect by increasing the cable network's vulnerability to future seismic events and to other sources of cable breaks (Yincan et al, 2018).

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

[13] And therefore it 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 & Murray, 2006).

- 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 for 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 increased by delays in cable repairs. According to Palmer-Felgate et al (2013), these delays vary significantly among maintenance areas and countries, and often result from multiple outages induced by natural events such as earthquakes or typhoons, from ships engaged in prior repairs (likely induced by multiple outages), and from repair permit acquisition delay and other operational issues (Borland, 2008; Yincan et al, 2018).

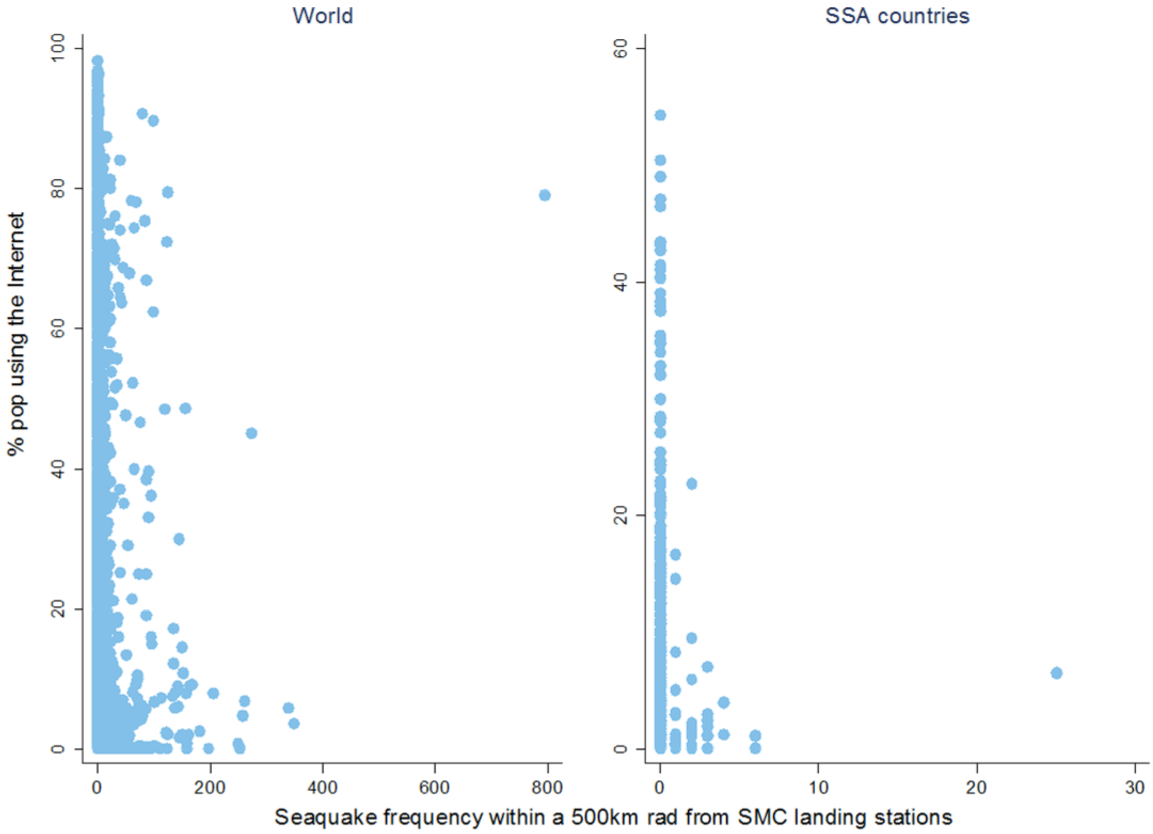
4.2. SSA infrastructure's exposure to seismic events

The SSA infrastructure's exposure to maritime seismic activity is documented in Table 5. Information on the location, timing, frequency and intensity of seaquakes is exploited to calculate the annual frequency of seaquakes that occurred within a radius of 500 km radius from SMC landing stations.[14] The data indicate that East Africa and, to a lesser extent, Central Africa are two sub-regions exposed to the risk of seaquake-induced cable outages. Therefore, SSA is exposed to damages on SMC faults that could induce substantial social and economic losses. Although this exposure is lesser than other developed and developing areas, it remains highly problematic for the subcontinent given the relatively low resilience of these countries due to the small number of SMCs connecting them to the world Internet.

Figure 7 below illustrates the negative correlation between Internet access and the exposure to maritime seismic events in SSA and the world. This correlation does not appear to be indirectly driven by differences in economic conditions between countries, as illustrated by the absence of graphical correlation between GDP per capita and SMC exposure to seaquakes in Appendix C.

[14] 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 in accordance with Soh et al (2004), who found that in the eastern part of Taiwan cable breaks occurred following earthquakes ranging from 5.0 to 6.0 on the Richter scale.

Figure 7. SMC exposure to seaquakes and Internet penetration, SSA and world evidence, 1990-2014.



Source: author. Data retrieved from ITU (2016), Telegeography and the Northern California Earthquake Data Center.

Table 5. 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
Comoros	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.

4.3. Estimating the impact of SMC's exposure to seismic events on the telecom sector

In this last empirical section, a multivariate econometric analysis of the impact of digital vulnerability, resulting from the SMC's exposure to seismic events, on ICTs is conducted on a sample of 46 SSA countries over 1990-2014. The *within* fixed-effect estimator is applied to the following specification:

$$ICT_{i,t} = \alpha_0 + \alpha_1.X_{i,t} + \alpha_2.SMC_{i,t} + \alpha_3.DIST_{i,t} + \alpha_4.VUL_{i,t} + \theta_i + \rho_t + \epsilon_{i,t} \quad (3)$$

Where $ICT_{\mathrm{i,t}}$ is the telecommunication sector's final or intermediary outcome variable in country *i* and year *t*, $X_{i,t}$ is the same vector of control variables as in equation (2), SMC_{it} and $DIST_{it}$ are respectively SMC deployment and digital isolation variables. VUL_{it} is the digital vulnerability to seismic risk variable, that is, the variable of interest. θ_i is the country fixed effect and ρ_t is the time fixed effect controlling for unobserved fixed country and time heterogeneity, and $\epsilon_{i,t}$ is an error term.

4.2.1. Data

Descriptive statistics, correlations between variables are provided in Appendix A. Variables' sources and definitions are provided in Appendix D. In the same way as in equation (2), telecommunication outcome variables (ICT_{it}) consist of two final outcome variables – the Internet and mobile penetration rates – and two intermediary outcome variables – the mobile cellular prepaid connection charge[15], and the annual number of fixed phone-line faults[16].

Again, control variables X_{it} are the same as in equation (2). In contrast to equation (2), equation (3) also includes a set of SMC-related control variables (SMC_{it}), to control for the characteristics of the SMC infrastructure affecting country's resilience to SMC faults. These controls are the number of SMCs by country, the total number of operators/investors sharing the ownership of SMCs hosted in a given country, and the number of years passed since the arrival of the first fiber-optic SMC in each country. Last, the geographical centroid distance to SMC ($DIST_{it}$) is also included to control for digital isolation.

The digital vulnerability variable (VUL_{it}) reflects the exposure to SMC outages induced by seismic activity. This risk variable is equal to the annual frequency of seaquakes of magnitude ranging between 5 and 6.5 on the Richter scale[17], which epicenter is located in the neighborhood of SMC landing stations. This variable is computed according to three different radiuses – 100, 500 and 1,000km – from SMC landing stations.

4.2.2. Results

The last round of estimations highlights the impact of the maritime infrastructure exposure to seismic risk, and is reported in Tables 6 and 7. The results show the negative impact of this source of digital vulnerability on telecom sector development, of stronger magnitude when the radius is set at 500 km from SMC landing stations. They support that one additional seaquake leads an approximate 0.12 percentage point decrease in Internet penetration rates. In columns (7) to (9), results stress that this effect is persistent through time, leading to a 0.23 percentage point decrease

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[15] This mobile prepaid tariff variable is preferred to other tariff variables such as mobile monthly subscription charge because of better data availability, and because it better reflects mobile phone usage in SSA.

[16] However, this variable does not fully reflect the overall network instability since faults that are not the responsibility of public operators are not recorded (see Appendix D).

[17] The lower bound has been chosen to ensure the magnitude is strong enough to challenge the infrastructure, based on the work of Soh et al. (2004) who find that cable breaks occurred in the eastern part of Taiwan following earthquakes ranging from 5.0 to 6.0 on the Richter scale. To exclude from the analysis seaquakes that could have indirectly impacted telecom outcomes through tsunamis, other physical damages or human casualties, an upper bound is chosen based on interviews with Dr Raphaël Paris, Research Officer in volcanology at CNRS and Laboratoire Magmas et Volcans (LMV) (Observatoire de Physique du Globe de Clermont-Ferrand, Clermont-Auvergne University), who pointed out that the risk of tsunami arises with seismic magnitude above 6.5 on the Richter scale. Levin and Nosov (2016) show that seaquake-induced tsunamis are generally triggered by underwater earthquakes with magnitude above 7.

in Internet penetration one year after the seaquake occurrence, and to a 0.21 percentage point decrease two years after. The specification with current and two-year lagged seismic variables is kept to study its effect on other telecommunication outcomes. Results in Table 7 confirm previous results, and show that SMC's exposure to seaquakes has a negative, significant and two-year lagging effect on mobile penetration, and a positive and significant effect on fixed phone-line faults.

Table 6. 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)
	Dep var: Internet penetration rate								
Seaquake freq 1000 km rad.	-0.0299	-0.0391							
	(-0.58)	(-0.57)							
Seaquake freq 500 km rad.			-0.123**	-0.164***			-0.096**	-0.116**	-0.0826*
			(-2.52)	(-5.97)			(-2.40)	(-2.55)	(-1.91)
Seaquake freq 100 km rad.					-0.119**	-0.160***			
					(-2.15)	(-3.58)			
Lag 1 Seaquake freq. 500km							-0.257***	-0.235***	-0.230***
							(-2.98)	(-2.97)	(-3.01)
Lag 2 Seaquake freq. 500km.								-0.212**	-0.159*
								(-2.42)	(-1.75)
Lag 3 Seaquake freq. 500km.									-0.384
									(-1.55)
Year dummies	Yes	No	Yes	Yes	No	Yes	Yes	No	Yes
Driscoll-Kraay standard errors	No	Yes	No	No	Yes	No	No	Yes	No
Controls	X_{it}, SMC_{it} $DIST_{it}$	X_{it}, SMC_{it} $DIST_{it}$	X_{it}, SMC_{it} $DIST_{it}$	X_{it}, SMC_{it} $DIST_{it}$	X_{it}, SMC_{it} $DIST_{it}$	X_{it}, SMC_{it} $DIST_{it}$	X_{it}, SMC_{it} $DIST_{it}$	X_{it}, SMC_{it} $DIST_{it}$	X_{it}, SMC_{it} $DIST_{it}$
N	920	920	920	920	920	920	920	920	920
# countries	46	46	46	46	46	46	46	46	46
R^2 (within)	0.738	0.683	0.739	0.684	0.738	0.684	0.740	0.742	0.742

t-student in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors are robust to heteroscedasticity, and robust to both heteroscedasticity and first-order autocorrelation in columns (2), (4), (6).

Table 7. 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)
	Mobile penetration rate			**Prepaid cellular connect. charge**			**# Fixed phone-line faults**		
Seaquake freq 500 km rad.	-1.147***	-1.514***	-1.131***	0.218	0.277	0.256	0.0647**	0.0860*	0.0823**
	(-4.30)	(-10.30)	(-4.57)	(0.92)	(1.67)	(1.02)	(2.20)	(1.87)	(2.24)
Lag 1 Seaquake freq			-1.244***			0.0334			-0.0335
			(-4.82)			(1.10)			(-0.64)
Lag2 Seaquake freq			-1.427***			0.0572			-0.0288
			(-4.96)			(1.31)			(-0.68)
Year dummies	Yes	No	Yes	Yes	No	Yes	Yes	No	Yes
Driscoll-Kraay standard errors	No	Yes	No	No	Yes	No	No	Yes	No
Controls	X_{it}, SMC_{it} $DIST_{it}$	X_{it}, SMC_{it} $DIST_{it}$	X_{it}, SMC_{it} $DIST_{it}$	X_{it}, SMC_{it} $DIST_{it}$	X_{it}, SMC_{it} $DIST_{it}$	X_{it}, SMC_{it} $DIST_{it}$	X_{it}, SMC_{it} $DIST_{it}$	X_{it}, SMC_{it} $DIST_{it}$	X_{it}, SMC_{it} $DIST_{it}$
N	920	920	846	218	218	218	433	433	403
# countries	46	46	46	44	44	44			
R^2 (within)	0.842	0.682	0.856	0.425	0.381	0.430	0.598	0.560	0.594

t-student in parenthesis. * p < 0.1, ** p < 0.05, *** p < 0.01. Standard errors robust to heteroscedasticity, and robust to both heteroscedasticity and first-order autocorrelation in columns (2), (5), (6).

5. Concluding remarks

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

In a first step, a diff-in-diff approach was followed to study the impact of the 2009 SEACOM and the 2010 MainOne and EASSy waves on the development of the ICT sector. Results stress that their arrival has yielded a 3-4 percentage point increase in Internet penetration rates in the subcontinent, corresponding to almost a doubling of the average Internet penetration rate in the subcontinent. This result is robust to various sample restrictions aimed to address sample selection bias. 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 international digital isolation.

This intuition is confirmed in a second step by a multivariate panel data analysis, focused on landlocked African countries, showing that the reduction in these countries' centroid or capital distances to coastal SMC landing stations has significantly increased Internet penetration and reduced the telecommunication network instability. This finding corroborates results of the literature on the geography of telecommunication infrastructures, which stresses that the digital divide in the periphery is partly explained by a higher vulnerability to telecommunication disruptions (Malecki, 2002; Grubesic et al, 2003; Gorman et al, 2004; Grubesic and Murray, 2006).

The issue of digital vulnerability is further addressed in a last step, and related to the SMCs' exposure to seismic events. Panel fixed-effect estimations are conducted on a sample of 46 coastal and landlocked African countries over 1990-2014, and indicate that an increase in the frequency of seaquakes in the neighborhood of SMC landing stations has negative and lasting impact on Internet penetration and on the telecommunication network stability.

All in all, this paper echoes in some way Malecki's (2002, p.399) view on the geography of the Internet infrastructure, in stressing that "interconnection is both critical to the functioning of the Internet and the source of its greatest complications".

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Appendixes

A. Variable sources, definition and descriptive statistics.

A.1. Descriptive statistics

Variable	Sources	Mean	Std. Dev.	Min	Max	Obs.	Countries
% pop using Internet	ITU	3.599857	6.63430	0	47.076	778	46
Ln mobile-cell prepaid subscript charge		2.267642	1.35749	0	9.72028	235	44
Ln # Fixed line faults		3.479371	1.34101	0.0296	7.06732	351	44
Ln # mobile subscript	WDI	20.88281	29.6036	0	179.471	773	46
Ln GDP/cap		6.592359	1.09821	4.6228	9.5389	778	46
% of 15–24yrs		54.16216	4.35247	47.403	71.45077	778	46
% urban pop		37.24095	16.4996	7.211	86.4576	778	46
Democracy status	Freedom House	2.105398	0.7187	1	3	778	46
2^{ary} Education index	Ferdi	28.79894	23.3536	0	100	778	46
Electricity access (%)	WDI/author	34.34615	24.9625	0.5558	100	778	46
# SMCs	Telegeography / Packet Clearing House	0.388175	0.85105	0	6	778	46
# IXPs		0.217224	0.53727	0	6	778	46
# SMC owners		4.46144	8.96147	0	59	778	46
# years since 1st SMC*	/ Packet Clearing House, and Peering DB databases	-1.661954	5.83605	-17	18	778	46
Ln demographic distance		6.627677	1.3532	0	8.55823	703	45
Ln geographic distance		6.7562	1.20816	0	8.56690	702	44
Ln capital distance		5.912122	2.57331	0	8.55783	699	46
Seaquake freq 500 km rad.		0.0989717	0.96621	0	25	778	46
Seaquake freq 100 km rad.		0.0488432	0.87445	0	24	778	46
Seaquake freq 1000 km rad.		0.3791774	1.54684	0	28	778	46
SMC outages		0.0257069	0.158361	0	1	778	46

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

A.2. Sample composition

Country Code	Freq. obs	Per cent	Country Code	Freq. obs	Per cent
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.3. Pairwise cross-correlations (1/2)

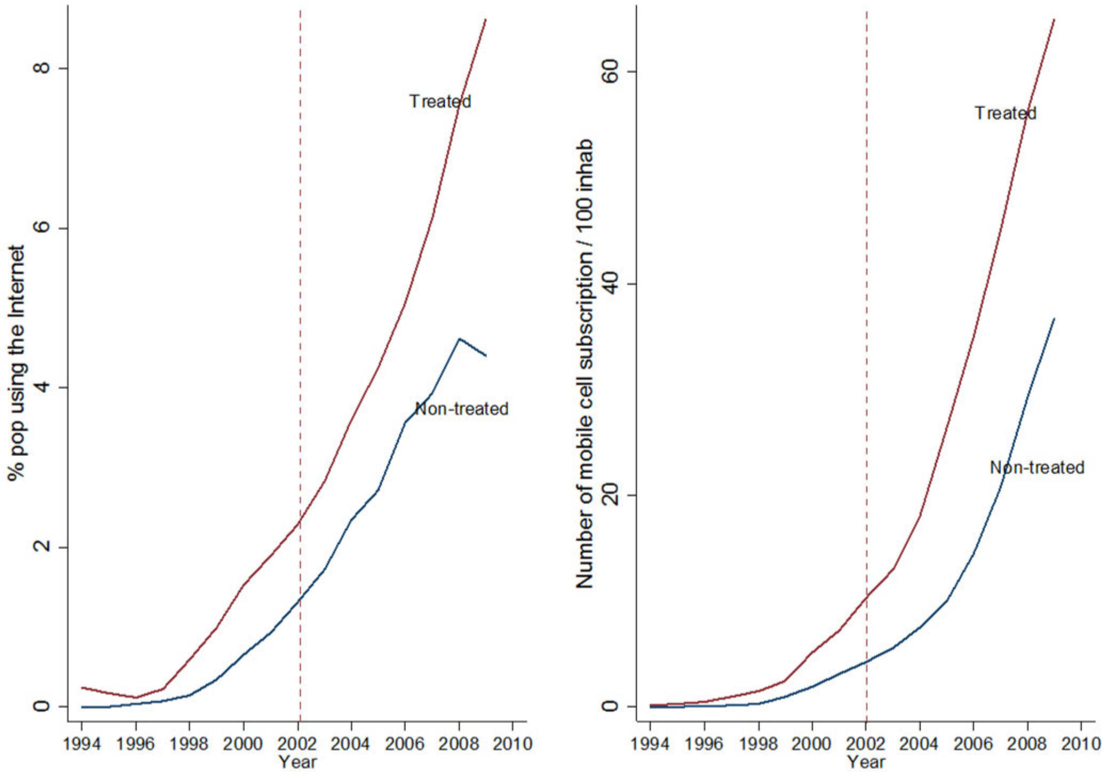
	% pop using Internet	Ln # mobile subscript	Cell repaid connect charge	Fixed line faults	# SMCs	# IXPs	# SMC owners	# years since 1st SMC	Seaquake freq 1000 km rad.
% pop using Internet	1								
% HH with fixed Internet	0.8409*								
Ln # mobile subscript	0.7163*	1							
Cell prepaid connect charge	-0.2746*	-0.4604*	1						
Fixed line faults	-0.3970*	-0.5429*	0.2543*	1					
# SMCs	0.5194*	0.4506*	-0.0831	-0.4043*	1				
# IXPs	0.4445*	0.3461*	-0.2807*	-0.1971*	0.4562*	1			
# SMC owners	0.4500*	0.4514*	-0.0521	-0.4160*	0.9341*	0.4028*	1		
# years since 1st SMC	0.3977*	0.4295*	-0.1075	-0.3958*	0.6370*	0.2763*	0.6614*	1	
Seaquake freq 1000 km	0.0279	0.0014	0.0399	0.0541	0.1198*	-0.0266	0.1084*	0.0397	1
Seaquake freq 500 km	-0.0252	-0.0388	0.1254	-0.0043	0.1194*	-0.0348	0.1050*	0.0761	0.7874*
Seaquake freq 100 km	0.0019	-0.0058	0.1116	0.0595	0.1407*	-0.019	0.1240*	0.1150*	0.4669*
SMC outages	0.0769	0.1361*	-0.0856	-0.1506*	0.1409*	0.1063*	0.1131*	0.1063*	-0.0045
Ln geo distance	-0.4575*	-0.4752*	-0.0177	0.3649*	-0.4574*	-0.0588	-0.4707*	-0.4579*	-0.2041*
Ln capital distance	-0.3503*	-0.4481*	-0.006	0.4530*	-0.5913*	-0.0781	-0.6740*	-0.5579*	-0.1503*
Ln demographic distance	-0.4521*	-0.4804*	-0.0331	0.3765*	-0.5182*	-0.0601	-0.5449*	-0.5126*	-0.2056*
Ln GDP/cap	0.4540*	0.4591*	-0.0876	-0.1601*	0.2402*	0.1798*	0.2717*	0.1129*	0.0436
% of 15–24yrs	0.5783*	0.5112*	-0.026	-0.2349*	0.2837*	0.2392*	0.2837*	0.1447*	0.1417*
% urban pop	0.2861*	0.3779*	-0.0006	-0.1265	0.3832*	0.0588	0.4515*	0.1526*	0.1217*
Democracy status	-0.2165*	-0.1658*	0.0365	0.1453*	-0.1141*	-0.1451*	-0.1613*	-0.1500*	0.0545
2^{ary} Education index	0.5811*	0.5648*	-0.1311	-0.3003*	0.3152*	0.3442*	0.3289*	0.1910*	-0.0107
Electricity access (%)	0.5028*	0.4637*	0.0539	-0.2130*	0.3504*	0.1612*	0.4038*	0.2419*	0.0892*
Being landlocked	-0.1265*	-0.1176*	-0.1182	0.0779	-0.3166*	0.0227	-0.3389*	0.1167*	-0.1792*

A.3. Pairwise cross-correlations (2/2)

	Seaquake freq 500 km	Seaquake freq 100 km	SMC outages	Geographic distance	Capital distance	Demographic distance	GDP/cap	% of 15–24yrs	% urban pop	Democracy status	2^{ary} Educ index	Electricity access (%)	Landlocked
Seaquake freq 500 km	1												
Seaquake freq 100 km	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	
Being landlocked	-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

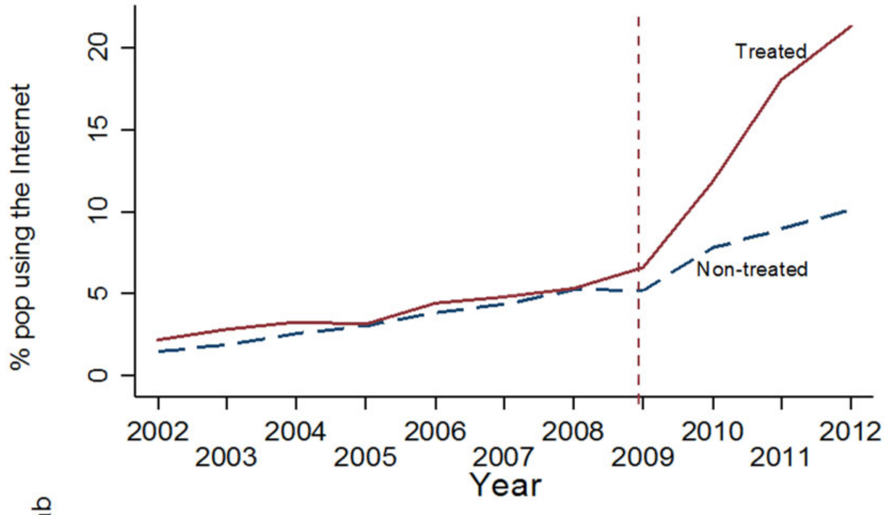
B. Parallel trend analysis: other regional waves of SMCs

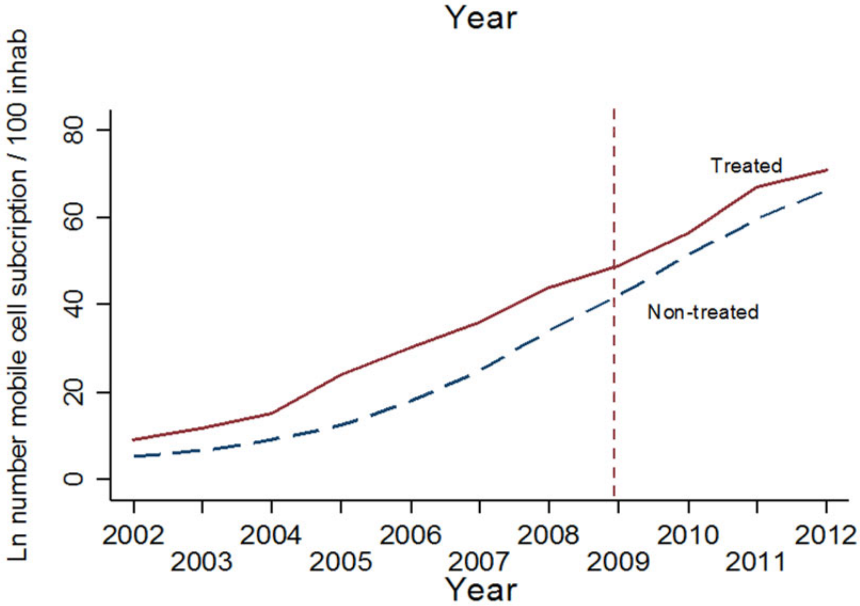
B.1. SAT3/SAFE (2002)



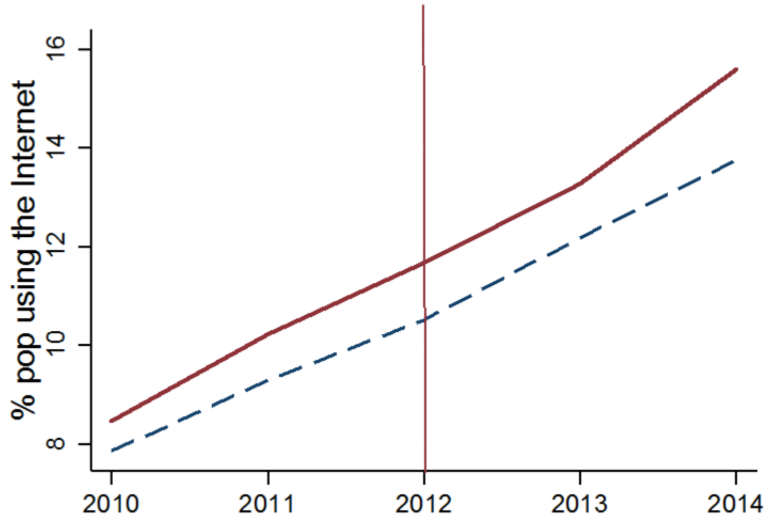
Note: Because of missing data, the evolution of other ICT variables in treated and non-treated groups is not reported.

B.2. SEACOM (2009)

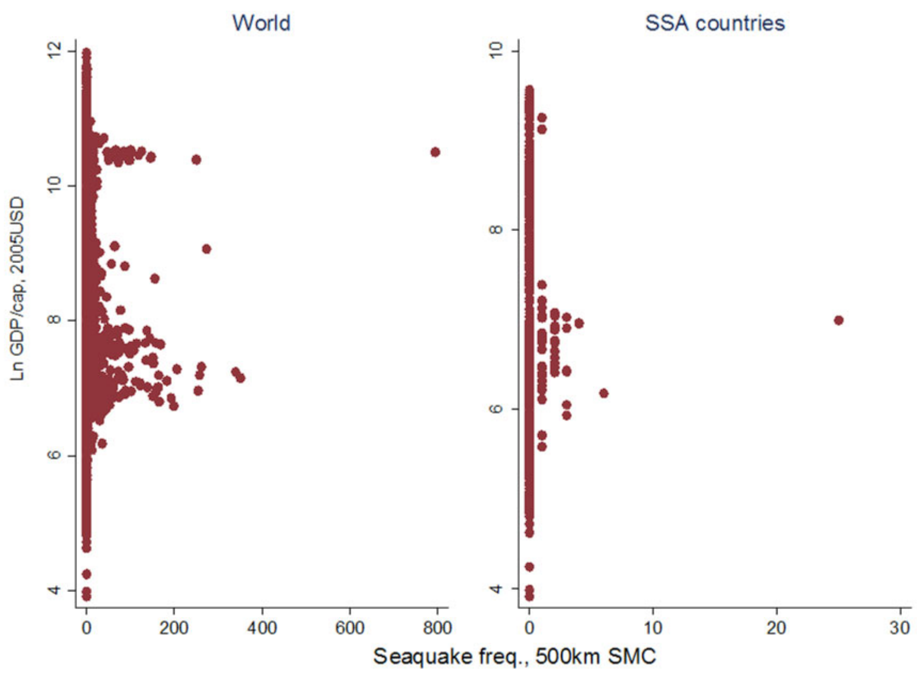




B.3. WACS/ACE (2012)



C. SMC exposure to seaquakes and the GDP/cap, SSA and world evidence, 1990-2014.



Source: author. . Data retrieved from WDI (2016), Telegeography and the Northern California Earthquake Data Center.

D. Data sources, definition, and treatment

D.1. Variable sources and definitions

Variable	Source	Definition
% pop using Internet	ITU	Percentage of individuals using the Internet
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 the connection charge). It should also be noted whether free minutes or free SMSs 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.
Fixed line faults	ITU	The total number of reported faults to fixed telephone lines for the year. Faults that 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 have been filled through linear interpolation and extrapolation, and transformed into an index between 0 and 1 by a minmax procedure (Feindouno & Goujon, 2016).
Electricity access (%)	World bank, author	Percentage of population with access to electricity. Electrification data are collected from industry, national surveys and international sources. Missing data have been inter- and extrapolated using five-year moving average.
# SMCs	Author, Telegeography	Number of submarine cables laid in a given country
# IXPs	Author Telegeography,	Number of Internet exchange points built in a given country

	Author, Packet Clearing House and Peering DB	
# 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 fibre-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 differs 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 500 km	Author, Telegeography, Northern California Earthquake Data Center	Annual number of seaquakes above 5 on the Richter scale within a 500 km radius from a country's SMC landing station
Seaquake freq 100 km	Author, Telegeography, Northern California Earthquake Data Center	Annual number of seaquakes above 5 on the Richter scale within a 1000 km radius from a country's SMC landing station
Seaquake freq 1000 km	Author, Telegeography, Northern California Earthquake Data Center	Annual number of seaquakes above 5 on the Richter scale within a 100 km radius from a country's SMC landing station

D.2. ICT infrastructure data collection and treatment

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 5 km 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 IXP** variables.

The number of years 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 the 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.

Digital isolation variables

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 the 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.

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.

"Sur quoi la fondera-t-il l'économie du monde qu'il veut gouverner? Sera-ce sur le caprice de chaque particulier? Quelle confusion! Sera-ce sur la justice? Il l'ignore."

Pascal

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