LIGHTNING, IT DIFFUSION, AND ECONOMIC GROWTH ACROSS U.S. STATES

Thomas Barnebeck Andersen, Jeanet Bentzen, Carl-Johan Dalgaard, and Pablo Selaya*

Abstract—Empirically, a higher frequency of lightning strikes is associated with slower growth in labor productivity across the 48 contiguous U.S. states after 1990; before 1990, there is no correlation between growth and lightning. Other climate variables (e.g., temperature, rainfall, and tornadoes) do not conform to this pattern. A viable explanation is that lightning influences IT diffusion. By causing voltage spikes and dips, a higher frequency of ground strikes leads to damaged digital equipment and thus higher IT user costs. Accordingly, the flash density (strikes per square kilometer per year) should adversely affect the speed of IT diffusion. We find that lightning indeed seems to have slowed IT diffusion, conditional on standard controls. Hence, an increasing macroeconomic sensitivity to lightning may be due to the increasing importance of digital technologies for the growth process.

I. Introduction

WE are by all accounts living in a time of global-climate changes. This is a good reason to explore the economic consequences of climate-related characteristics. In particular, how does the climate influence the growth process?

There seems to be compelling evidence to suggest that climate and geography profoundly affected the historical growth record (Diamond, 1997; Olsson & Hibbs, 2005; Putterman, 2008; Ashraf & Galor, 2008). Today, climate shocks, like temperature changes, still affect growth in poor countries (Dell, Jones, & Olken, 2008). But are climate and geography also important in highly developed economies, where high-tech industry and services are dominant activities?

Some research suggests that geography is still a force to be reckoned with, even in rich places. Access to waterways, for instance, appears to matter (Rappaport & Sachs, 2003). However, a geographic characteristic that exhibits a time-invariant impact on prosperity is difficult to disentangle from other slow-moving growth determinants that may have evolved under the influence of climate or geography. In particular, climate and geography probably influenced the evolution of economic and political institutions.[1]

This paper documents that a particular climate-related characteristic, lightning activity, exhibits a time-varying impact on growth in the world's leading economy. Studying the growth process across the 48 contiguous U.S. states from 1977 to 2007, we find no impact from lightning on growth prior to about 1990. However, since 1990, there has been a strong negative association: states where lightning occurs at higher frequencies have grown relatively more slowly. What can account for an increasing macroeconomic sensitivity to lightning?

In addressing this question, we begin by noting that the 1990s was a period of comparatively rapid U.S. growth, where the productivity slowdown appears to finally have come to an end. Furthermore, the 1990s is the period during which IT appears to have diffused throughout the U.S. economy at a particularly rapid pace. In fact, IT investment is often seen as a key explanation for the U.S. growth revival (Jorgenson, 2001). On a state-by-state basis, however, the process of IT diffusion (measured by per capita computers and Internet users, as well as manufacturing firms' IT investments) did not proceed at a uniform speed.

An important factor that impinges on IT investment and diffusion is the quality of the power supply. That a high-quality power supply is paramount for the digital economy is by now widely recognized. As observed in *The Economist*:[2]

> For the average computer or network, the only thing worse than the electricity going out completely is power going out for a second. Every year, millions of dollars are lost to seemingly insignificant power faults that cause assembly lines to freeze, computers to crash and networks to collapse.... For more than a century, the reliability of the electricity grid has rested at 99.9%.... But microprocessor-based controls and computer networks demand at least 99.9999% reliability ... amounting to only seconds of allowable outages a year.

Indeed, a sufficiently large power spike lasting only 1 millisecond is enough to damage solid-state electronics such as microprocessors in computers. Therefore, as a simple matter of physics, an irregularly fluctuating power supply reduces the longevity of IT equipment and increases the user cost of IT capital.

A natural phenomenon that causes irregular voltage fluctuations is lightning activity. Albeit the impulse is of short duration, its size is impressive. Even in the presence of lightning arresters on the power line, peak voltage emanating from a lightning strike can go as high as 5,600 V, which far exceeds the threshold for power disruptions beyond

Received for publication March 1, 2010. Revision accepted for publication February 24, 2011.

* Andersen: Department of Business and Economics, University of Southern Denmark; Bentzen, Dalgaard, and Selaya: Department of Economics, University of Copenhagen.

We thank an anonymous referee, Daron Acemoglu, Roland Benabou, Michael Burda, Raquel Fernandez, Oded Galor, Norman Loayza, Heino Bohn Nielsen, Ariel Reshef, Jon Temple, Ragnar Torvik, David Weil, Joseph Zeira, and seminar participants at University of Birmingham, Brown University, the 2009 NBER summer institute, the 2009 Nordic Conference in Development Economics, the third Nordic Summer Symposium in Macroeconomics, NTNU Trondheim, University of Southern Denmark, and the Tenth World Congress of the Econometric Society for comments and suggestions.

An online appendix is available at http://www.mitpressjournals.org/doi/suppl/10.1162/REST_a_00316.

[1] An apparent impact from diseases on comparative development may be convoluting the impact from early property rights institutions in former colonies (Acemoglu et al., 2001). The impact of access to waterways, as detected in cross-country data, may also be related to the formation of institutions (Acemoglu, Johnson, & Robinson, 2005).

[2] "The Power Industry's Quest for the High Nines," *Economist*, March 22, 2001.

The Review of Economics and Statistics, November 2012, 94(4): 903–924

which connected IT equipment starts being damaged (Emanuel & McNeil, 1997). Moreover, the influence from lightning is quantitatively important. To this day, lightning activity causes around one-third of the total number of annual power disruptions in the United States (Chisholm & Cummins, 2006). Theoretically, it is therefore very plausible that lightning may importantly have increased IT user costs.[3] Consequently, in places with higher IT user cost, one would expect a slower speed of IT diffusion; lightning-prone regions may be facing a climate-related obstacle to rapid IT diffusion. It is worth observing that the problems associated with lightning activity, in the context of IT equipment, have not gone unnoticed by the private sector. As the *Wall Street Journal* reports:[4]

> Even if electricity lines are shielded, lightning can cause power surges through unprotected phone, cable and Internet lines—or even through a building's walls. Such surges often show up as glitches. "Little things start not working; we see a lot of that down here," says Andrew Cohen, president of Vertical IT Solutions, a Tampa information-technology consulting firm. During the summer, Vertical gets as many as 10 calls a week from clients with what look to Mr. Cohen like lightning-related problems. Computer memory cards get corrupted, servers shut down or firewalls cut out.

Although a link between lightning and IT diffusion is plausible, it does not follow that the link is economically important in the aggregate. Nor is it obvious that IT can account for the lightning-growth correlation.

We therefore also study the empirical link between lightning and the spread of IT across the United States. IT is measured from both the household side (Internet and computer use) and the firm side (manufacturing firms' IT investment rates). We find that the diffusion of IT has progressed at a considerably slower pace in areas characterized by a high frequency of lightning strikes. This link is robust to the inclusion of a large set of additional controls for computer diffusion. Moreover, lightning ceases to be correlated with growth after 1990 once controls for IT are introduced. While the lightning-IT-growth hypothesis thus seems well founded, other explanations cannot be ruled out a priori.

An alternative explanation is that the correlation between growth and lightning picks up growth effects from global warming. If global warming has caused lightning to increase over time and simultaneously worked to reduce productivity growth, this could account for the (reduced-form) correlation between lightning and growth. We document that this is unlikely to be the explanation for two reasons. First, we show that from 1906 onward, US aggregate lightning is stationary; on a state-by-state basis, we find the same for all save two states. There is thus little evidence to suggest that lightning density is influenced by a global warming–induced trend. Second, we attempt to deal with the potential omitted variables problem by controlling directly for climate shocks, which also could be induced by climate change. We examine an extensive list of climate variables, including rainfall, temperature and frequency of tornadoes. None of these variables has an impact on the correlation between lightning and state-level growth rates. Nor does any other climate variable exhibit the kind of time-varying impact on growth that we uncover for lightning.

Another potential explanation is that the lightning-growth correlation is picking up deep determinants of prosperity that exhibit systematic variation across climate zones, just as lightning does—for instance, settler mortality rates, the extent of slavery, and so forth. However, the correlation between lightning and growth is left unaffected by their inclusion in the growth regression.

In sum, we believe the most likely explanation for the lightning-growth correlation is to be found in the diffusion mechanism. The analysis therefore provides an example of how technological change makes economies increasingly sensitive to certain climate-related circumstances. This finding is consistent with the temperate drift hypothesis (Acemoglu, Johnson, & Robinson, 2002), which holds that certain climate-related variables may influence growth in some states of technology and not (or in the opposite direction) in others.

The paper is related to the literature that studies technology diffusion, particularly the diffusion of computers and the Internet (Caselli & Coleman, 2001; Beaudry, Doms, & Lewis, 2006; Chinn & Fairlie, 2007). In line with previous studies, we confirm the importance of human capital for the speed of IT diffusion. However, the key novel finding is that climate-related circumstances matter as well: lightning influences IT diffusion. In this sense, the paper complements the thesis of Diamond (1997), who argues for an impact of climate on technology diffusion. Yet whereas Diamond argues that climate is important in the context of agricultural technologies, this paper makes plausible that climate also matters to technology diffusion in high-tech societies.

The analysis proceeds as follows. In the next section we document the lightning-growth link. In section III, we discuss likely explanations (IT diffusion, other forms of climatic influence, institutions, and integration) for the fact that lightning correlates with growth from about 1990 onwards. Section IV concludes.

II. Lightning and U.S. Growth 1977–2007

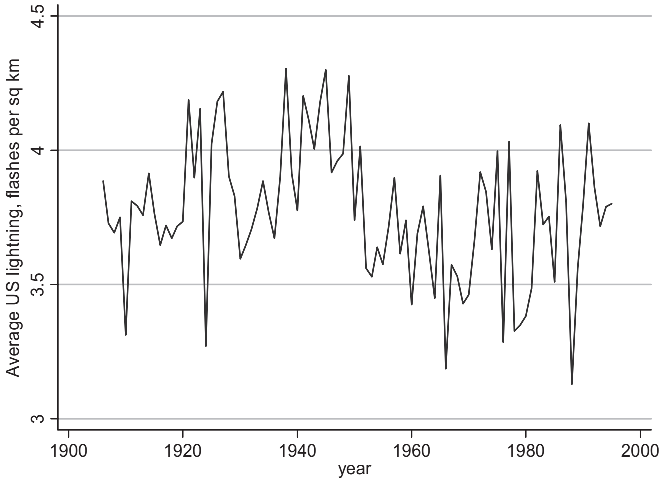
This section falls in two parts. In section IIA, we present the data on lightning and discuss its time series properties. In particular, we demonstrate that lightning is stationary

---

[3] Naturally, the "power problem" may be (partly) addressed, but only at a cost. The acquisition of surge protectors, battery backup emergency power supply (so-called uninterruptable power supply), and the adoption of a wireless Internet connection will also increase IT user costs through the price of investment. Hence, whether the equipment is left unprotected or not, more lightning-prone areas should face higher IT user cost.

[4] "There Go the Servers: Lightning's New Perils," *Wall Street Journal*, August 25, 2009.

FIGURE 1.—AVERAGE FLASH DENSITY IN THE UNITED STATES FOR FORTY STATES



Lightning observations from weather stations, transformed from thunder days (TD) into flash density (FD) using the formula $FD = 0.04 \times TD^{1.25}$.

Only 40 states have complete information for the period 1906 to 1995. The "left-out" (contiguous) states are Connecticut, Delaware, New Hampshire, New Jersey, Rhode Island, Vermont, Mississippi, and West Virginia. The figure shows the weighted average, where the weight is determined by state size. See the online appendix for details.

and that for panel data purposes, it is best thought of as a state fixed effect. Next, in section IIB, we study the partial correlation between lightning and growth across the U.S. states.

A. *The Lightning Data*

The measure of lightning activity that we employ is the flash density, which captures the number of ground flashes per square kilometer per year. We have obtained information about the flash density from two sources. The first source of information is reports from weather stations around the United States. From this source, we have yearly observations covering the period 1906–1995 and 40 U.S. states. From about 1950 onward, we have data for 42 states. The second source of information derives from ground censors around the United States. These data are a priori much more reliable than the data from weather stations.[5] In addition, they are available for all 48 contiguous states, but they come only as an average for the period 1996 to 2005.[6]

In order to understand the data better, we begin by studying its time series properties. Figure 1 shows the time path for aggregate U.S. lightning over the period 1906 to 1995. The aggregate flash density is calculated as the state-size weighted average over the 40 states with data for this extended period. Visual inspection suggests that there is no time trend. To test whether lightning contains a stochastic trend, we use an augmented Dickey-Fuller (DF) test with no deterministic trend. Lag length is selected by minimizing the Schwarz information criterion with a maximum of five lags. For aggregate U.S. lightning, the optimal lag length is 1, and the DF statistic equals −4.516. Hence, the presence of a unit root is resoundingly rejected.

TABLE 1.—DICKEY-FULLER TESTS FOR UNIT ROOT IN LIGHTNING

	Test Statistic	*p*-Value	Number of Observations.	Number of Lags
Aggregate U.S.	−4.52	0.0000	88	1
Alabama	−5.31	0.0000	88	1
Arizona	−3.38	0.0118	87	2
Arkansas	−8.98	0.0000	89	0
California	−8.40	0.0000	89	0
Colorado	−8.69	0.0000	89	0
Florida	−8.19	0.0000	89	0
Georgia	−8.58	0.0000	89	0
Idaho	−3.48	0.0085	87	2
Illinois	−9.61	0.0000	89	0
Indiana	−8.24	0.0000	89	0
Iowa	−9.42	0.0000	89	0
Kansas	−4.46	0.0002	88	1
Kentucky	−2.94	0.0412	87	2
Louisiana	−4.62	0.0001	88	1
Maine	−2.75	0.0662	87	2
Maryland	−5.32	0.0000	88	1
Massachusetts	−9.25	0.0000	89	0
Michigan	−8.76	0.0000	89	0
Minnesota	−10.28	0.0000	89	0
Missouri	−9.92	0.0000	89	0
Montana	−9.01	0.0000	89	0
Nebraska	−3.64	0.0051	87	2
Nevada	−10.02	0.0000	89	0
New Mexico	−3.58	0.0062	87	2
New York	−4.01	0.0013	88	1
North Carolina	−5.40	0.0000	88	1
North Dakota	−7.84	0.0000	89	0
Ohio	−3.59	0.0059	87	2
Oklahoma	−11.61	0.0000	89	0
Oregon	−7.09	0.0000	89	0
Pennsylvania	−2.20	0.2045	86	3
South Carolina	−8.01	0.0000	89	0
South Dakota	−8.62	0.0000	89	0
Tennessee	−7.32	0.0000	89	0
Texas	−5.45	0.0000	88	1
Utah	−5.55	0.0000	88	1
Virginia	−7.41	0.0000	89	0
Washington	−8.75	0.0000	89	0
Wisconsin	−9.45	0.0000	89	0
Wyoming	−7.71	0.0000	89	0

The augmented Dickey-Fuller test with no deterministic trend for each of the forty states over the period 1906–1995. Lags selected by Schwarz's information criteria. Lightning is the average number of flashes per year per square kilometer, measured at weather stations.

At the state level the presence of a unit root is also rejected at the 5% level in 38 of the 40 states, (see table 1). In light of the fact that DF tests have low power to reject the null of a unit root (even more so when, as here, we do not include a deterministic trend), we are in all likelihood safe to conclude that state-level lightning is also stationary.

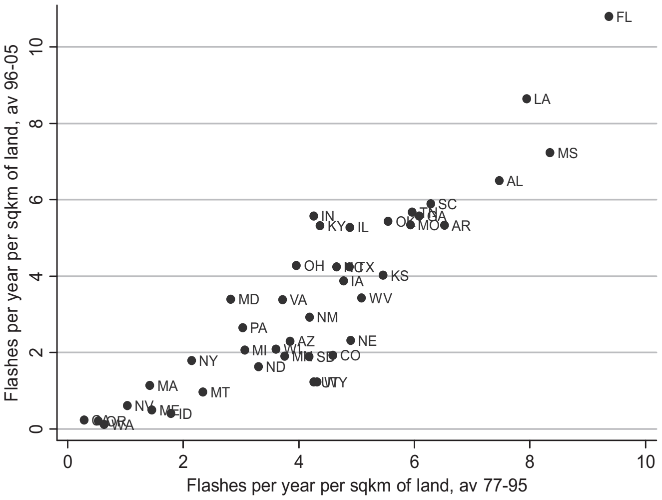
These findings are of some independent interest in that they suggest that global warming has not interfered with the evolution of lightning trajectories in the United States in recent times. In other words, there is little basis for believing that the flash density has exhibited a trend during the past century.

---

[5] Lightning events recorded at weather stations are based on audibility of thunder (basically recordings of thunder days), whereas ground sensors measure the electromagnetic pulse that emanates from lightning strikes (recordings of actual ground strikes). In the context of IT diffusion, it is ground strikes that matter, not say, the type of lightning occurring between clouds.

[6] Further details are given in the online appendix.

FIGURE 2.—AVERAGE FLASH DENSITY 1977–1995 VERSUS 1996–2005: FORTY-TWO STATES



1977–1995 Based on thunder days (TD) from weather station observations, converted into flash density (FD) using the formula FD = 0.04 × $TD^{1.25}$. 1996–2005: Based on ground detectors. The correlation is 0.90, and a regression, $FL_{96\text{–}05} = a + bFL_{77-95}$ returns: $a = -0.99$, $b = 1.05$, and $R^2 = 0.81$. See the online appendix for further details.

In the analysis, we focus on the period from 1977 onward, dictated by the availability of data on gross state product. Consequently, it is worth examining the time series properties of the lightning variable during these last few decades of the twentieth century.

During this period, the flash density is for all practical purposes a fixed effect. In the online appendix, table A.1, we show state by state that the residuals obtained from regressing lightning on a constant are serially uncorrelated. That is, deviations of the flash density from time averages are, from a statistical perspective, white noise. To show this formally, we use the Breusch-Godfrey test and a Runs test for serial correlation. By the standards of the Breusch-Godfrey test, we cannot reject the null hypothesis of no serial correlation in 38 out of 42 states; using the Runs test, we fail to reject the null in 40 states. Importantly, no state obtains a *p*-value below 0.05 in both tests. This suggests that for the 1977–1995 period, lightning is best described as a state fixed effect.

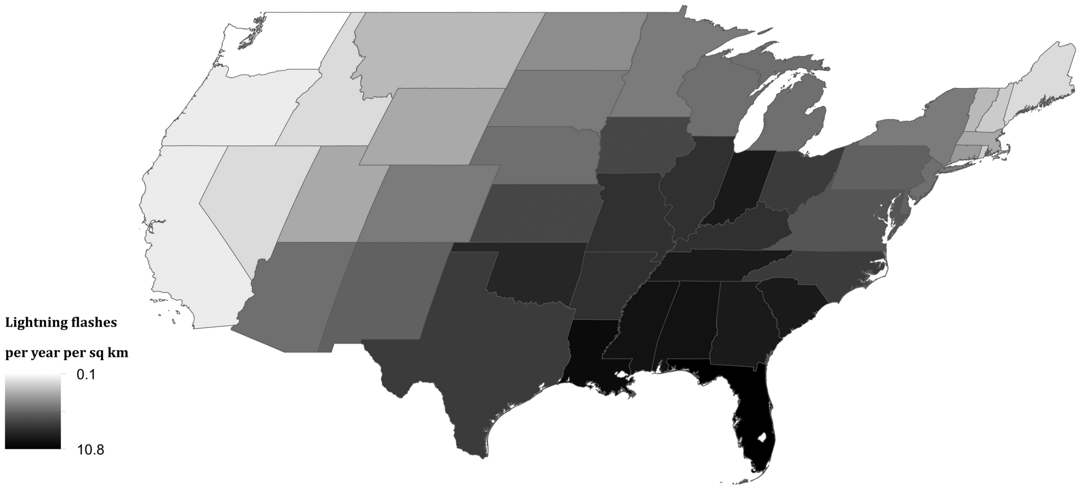
We have an alternative source of data available to us, which contains information for the 1996–2005 period. How much of a concurrence is there between data for the 1977–1995 period and the data covering the end of the 1990s and early years of the twenty first century? Figure 2 provides an answer. The figure reveals that the two measures are very similar. In fact, we cannot reject the null that the slope of the line is equal to 1. This further corroborates that lightning is a state fixed effect.

These findings have induced us to rely on the data deriving from ground censors in the analysis. As we have noted, these latter lightning data are of a higher quality compared to the measure based on weather stations and cover more U.S. states. Moreover, since deviations from the average flash density are white noise, we lose no substantive information by resorting to a time-invariant measure. Still, it should be stressed that using instead the historical lightning measure based on weather stations (or combining the data) produces the same (qualitative) results as those reported below. (These results are available on request.)

The cross-state distribution of the 1996–2005 data is shown in figure 3, and summary statistics for 1996 to 2005 are provided in table 2.

There is considerable variation in the flash density across states. At the lower end are Washington, Oregon, and California with less than one strike per square kilometer per year. It is interesting to note that the two states that are world famous for IT, Washington and California, are among the least lightning prone. At the other end of the spectrum are Florida, Louisiana, and Mississippi, with seven strikes or more. It is clear that lightning varies systematically across climate zones. Hence, it is important to check, as we do below, that lightning's correlation with growth is not due to

FIGURE 3.—DISTRIBUTION OF FLASH DENSITIES ACROSS THE UNITED STATES, 1996–2005



Source: Own calculations based on data from U.S. National Lightning Detection Network Database (NLDN). See details in the online appendix.

TABLE 2.—SUMMARY STATISTICS FOR THE MAIN VARIABLES

	Observations	Mean	s.d.	Percentiles 99%	75%	50%	25%	1%
Average annual growth rate of real GSP per worker (%)								
1977–1987	48	0.81	0.77	2.69	1.32	0.74	0.30	−0.76
1987–1997	48	1.21	0.58	2.67	1.50	1.22	0.82	−0.32
1997–2007	48	1.18	0.54	2.59	1.49	1.15	0.74	0.26
1977–2007	48	1.07	0.42	1.97	1.37	1.07	0.82	0.10
1991–2007	48	1.34	0.50	2.79	1.71	1.35	1.01	0.29
Lightning density, average 1996–2005 (flashes/year/sq km)	48	3.18	2.39	10.79	5.30	2.48	1.23	0.12
Manufacturing firms' IT investments, 2007 (% of nonconstruction capital expenditures)	48	5.40	2.20	10.19	7.17	4.78	3.51	1.31
Access to Internet at home, 2003 (% of households)	48	54.39	5.88	65.50	58.10	55.00	51.20	39.50
Computer at home, 2003 (% of households)	48	62.10	5.71	74.10	66.25	61.85	58.95	48.80

Lightning defined as average number of flashes per year per square kilometer over the period 1996 to 2005, measured by flash detectors. IT capital expenditures defined as capital expenditures on computers and peripheral data processing equipment in all manufactuting firms in 2007, expressed as a percentage of all nonconstruction capital expenditures. Data sources and extended definitions are provided in the online appendix.

FIGURE 4.—CORRELATION BETWEEN STATE GROWTH AND (LOG) FLASH DENSITY, CONDITIONAL ON INITIAL INCOME PER WORKER, 1977–1992

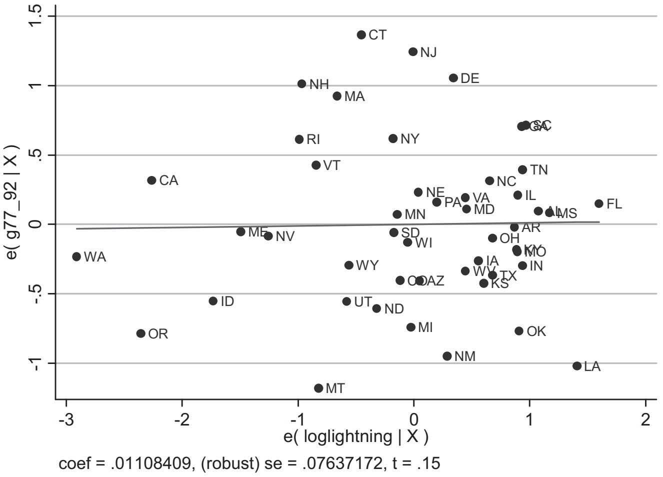
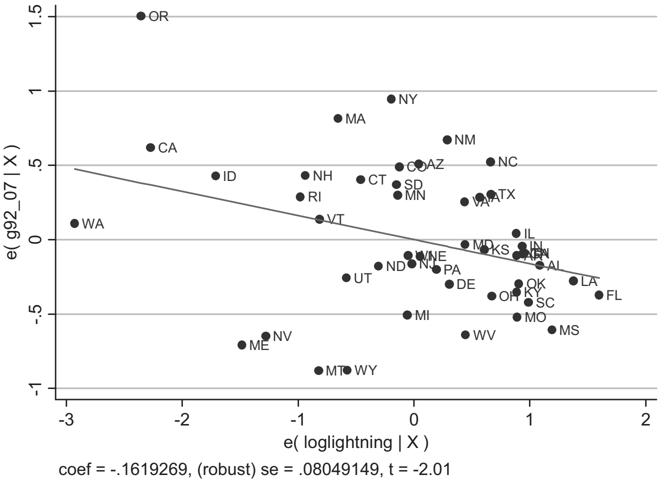


FIGURE 5.—CORRELATION BETWEEN STATE GROWTH AND (LOG) FLASH DENSITY, CONDITIONAL ON INITIAL INCOME PER WORKER, 1992–2007



other climate variables like high winds, rainfall, and so on and that spatial clustering effects are not deflating standard errors.

B. Emergence of a Lightning-Growth Nexus

Figures 4 and 5 show the partial correlation between growth in labor productivity and the flash density, controlling only for initial labor productivity.

We have data on gross state product (GSP) per worker for the period 1977 to 2007.[7] Hence, for this first exercise, we have simply partitioned the data into two equal-sized fifteen-year epochs. As seen from the two figures, there is a marked difference in the partial correlation depending on which subperiod we consider. During the 1977–1992 period, there is no association between growth and lightning; the (OLS) point estimate is essentially nil. However, in the second period, the coefficient for lightning rises twenty-fold (in absolute value) and turns statistically significant; places with higher flash density have tended to grow at a slower rate during the 1990s and the first decade of the twenty first century.

While this exercise is revealing, there is no particular reason to believe that the lightning-growth correlation emerged precisely in 1992. Hence, to examine the issue in more detail, we study the same partial correlation by running rolling regressions over ten-year epochs, starting with 1977 to 1987.[8] That is, letting G_{it} denote the percentage average annual (continuously compounded) growth rate of GSP per worker over the relevant ten-year epoch,[9] we estimate an equation of the following kind,

$$G_{it} = b_0 + b_1 \log(y_{it-10}) + b_2 \log(lightning_i) + \varepsilon_i,$$

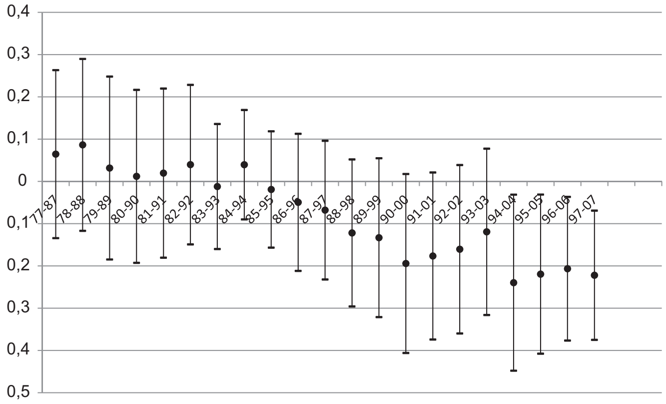
---

[7] State-level data on personal income are also available, and for a longer period. But personal income does not directly speak to productivity. By contrast, GSP per worker is a direct measure of state-level labor productivity. Moreover, the GSP per worker series is available in constant chained dollar values, an important advantage in the context of dynamic analysis. See the online appendix for a description of the GSP per worker series.

[8] The exact choice of time horizon does not matter much; below we run regressions with five-, ten-, and fifteen-year epochs that complement the exercise in this paper.

[9] That is, $G_{\text{it}} = 100 \times (1/T) \times \log(y_{\text{it}}/y_{\text{it}-\text{T}})$, where $T = 10$.

FIGURE 6.—LIGHTNING-GROWTH NEXUS, 1977–2007



The figure shows estimates for b_2 (and the associated 95% confidence interval) from regressions of the form: $G = b_0 + b_1\log(y_{t-10}) + b_2\log(\text{lightning}) + e$, where y is gross state product per worker and t = 1987,. . ., 2007. For 48 states; estimated by OLS.

and examine the evolution of b_2 as t increases. Figure 6 shows the time path for b_2, as well as the associated 95% confidence interval.

At the beginning of the period, there is not much of a link between lightning and growth; if anything, the partial correlation is positive. As one moves closer to the 1990s, the partial correlation starts to turn negative and grows in size (absolute value). By 1995, the lightning-growth correlation is statistically significant at the 5% level of confidence. As one moves forward in time, the partial correlation remains stable and significant. Hence, this exercise points to the same conclusion as that suggested by figures 4 and 5: the negative partial correlation between lightning and growth emerged in the 1990s.

Albeit illustrative, the two exercises conducted so far are ad hoc in the sense that they do not allow a formal test of whether the impact from lightning is rising over time. Hence, as a final check, we run panel regressions with period length of five, ten, and fifteen years. The results are reported in table 3.

Since lightning, for all practical purposes, is a fixed effect (see section IIA), table 3 reports the results from running pooled OLS regressions. Specifically, we estimate the following growth regression:

$$G_{it} = b_0 + b_1\log(y_{it-T}) + b_{2t}\log(lightning_i) + \mu_t + \varepsilon_{it},$$

where $T = 5$, 10, 15 and b_{2t} accordingly is allowed to vary from period to period by way of interaction with time dummies. In this way, we can track the statistical and economic significance of lightning over time. Note also that we include time dummies independent of lightning so as to capture a possible secular trend in growth over the period in question.

Turning to the results, we find that the impact of lightning increases over time and turns statistically significant during the 1990s.[10] The significance of lightning is particularly noteworthy as it is obtained for the relatively homogeneous sample of U.S. states. As is well known, the growth process for this sample is usually fairly well described by the initial level of income alone, suggesting only modest variation in structural characteristics that impinge on long-run labor productivity (Barro & Sala-i-Martin, 1992). As a result, the scope for omitted variable bias contaminating the OLS estimate for lightning is a priori much more limited than, say, in a cross-country setting.

Still, a potential concern is that the lightning-growth correlation could be due to the omission of human capital. As is well known, the return on skills appears to have risen during the 1990s, which could suggest an increasing effect from education on growth. If, in addition, the level of education is negatively correlated with lightning intensity (and it is), the lightning-growth link might disappear once schooling is introduced.

In table 4 we therefore add measures of human capital to the growth regression. In order to do so rigorously, we add information on primary, secondary, and tertiary education simultaneously. Because the lightning correlation does not depend appreciably on whether we invoke five-, ten-, or fifteen-year epoch length we have chosen to focus on ten-year epochs. (Results for five- and fifteen-year epochs are similar, and available on request.)

Columns 2 to 5 of the table reveal that the human capital measures have no bearing on the lightning-growth correlation relative to the baseline growth regression in column 1; lightning is always significant regardless of whether the three human capital proxies are added one by one (see columns 2–4) or included jointly (see column 5).

Another concern relates to regional effects. As is visually clear from figure 3, lightning density is characterized by a certain degree of geographical clustering. Such cluster effects may impinge on the analysis in several ways.[11] Most important, one may worry that the lightning-growth correlation simply reflects that the Southeast, a high-lightning area, is growing more slowly for reasons unrelated to lightning during this period. This suggests that we should add regional fixed effects to the growth regression.

In this endeavor we rely on the economic areas classification used by the Bureau of Economic Analysis (BEA), which distinguishes eight regions.[12] This classification is, however, taxing on our results in the sense that regressing the eight BEA areas on (log) lightning explains 84% of the cross-state lightning variation (see the online appendix, table A.2, column 4).

In column 6 of table 4, we add the eight regional fixed effects. The inclusion of the BEA regions does not impinge on the size of the partial correlation between lightning and growth, but it does on the precision of the OLS estimate in

---

[10] The general time dummies (not reported) corroborate the prior of a revitalization of productivity growth during the 1990s.

[11] See Cameron and Trivedi (2005) or Angrist and Pischke (2009) for general discussions of clustering.

[12] The eight BEA regions are Far West, Great Lakes, Mideast, New England, Plains, Rocky Mountain, Southeast, and Southwest.

TABLE 3.—GROWTH AND LIGHTNING

A: Five-Year Periods: Regression 1

1977–1982	1982–1987	1987–1992	1992–1997	1997–2002	2002–2007	Observations	R^2
−0.04	0.17	−0.09	−0.04	−0.28**	−0.18*	288	0.20
[0.10]	[0.16]	[0.09]	[0.12]	[0.11]	[0.09]		

B: Ten-Year Periods: Regression 2

1977–1987	1987–1997	1997–2007	Observations	R^2
0.07	−0.07	−0.22***	144	0.15
[0.10]	[0.08]	[0.08]		

C: Fifteen-Year Periods: Regression 3

1977–1992	1992–2007	Observations	R^2
0.01	−0.16**	96	0.20
[0.08]	[0.08]		

Pooled OLS estimates of the coefficient on lightning (b_2t). The dependent variable in regressions 1, 2 and 3 is the yearly average growth rate in GSP per worker over periods of five, ten, and fifteen years, respectively. All regressions include a constant, the initial level of (log) real GSP per worker, and a full set of time dummies. Lightning is the average number of flashes per year per square kilometer, measured by flash detectors. Robust standard errors in brackets, adjusted for clustering at the state level. Significant at the ***1%, **5%, and *10%, levels.

TABLE 4.—GROWTH AND LIGHTNING, CONTROLLING FOR HUMAN CAPITAL AND REGIONAL FIXED EFFECTS

Dependent Variable	Average Annual Growth in GSP per Worker over Periods of Ten Years (1977–1987, 1987–1997, 1997–2007)					
	(1)	(2)	(3)	(4)	(5)	(6)
(log, initial) Real GSP per worker	−0.72	−1.24***	−0.60	−1.25***	−1.80***	−1.97***
	[0.45]	[0.41]	[0.46]	[0.44]	[0.41]	[0.54]
(log) Lightning × t_{77-87}	0.07	−0.04	−0.14	0.13	−0.12	−0.04
	[0.10]	[0.11]	[0.12]	[0.11]	[0.11]	[0.15]
(log) Lightning × t_{87-97}	−0.07	−0.16**	−0.07	0.03	−0.12	−0.05
	[0.08]	[0.07]	[0.09]	[0.08]	[0.08]	[0.14]
(log) Lightning × t_{97-07}	−0.22***	−0.24***	−0.22**	−0.13*	−0.21**	−0.17
	[0.08]	[0.08]	[0.09]	[0.08]	[0.08]	[0.14]
(initial) Enrollment rate × t_{77-87}		−0.07***			−0.06***	−0.04*
		[0.02]			[0.02]	[0.02]
(initial) Enrollment rate × t_{87-97}		−0.07***			−0.07***	−0.05*
		[0.02]			[0.02]	[0.03]
(initial) Enrollment rate × t_{97-07}		−0.03			−0.01	0.01
		[0.02]			[0.02]	[0.02]
(initial) High school diploma or higher × t_{77-87}			−0.04***		−0.06***	−0.05***
			[0.01]		[0.02]	[0.02]
(initial) High school diploma or higher × t_{87-97}			−0.0016		−0.02	−0.01
			[0.015]		[0.02]	[0.02]
(initial) High school diploma or higher × t_{97-07}			−0.00076		−0.05**	−0.03
			[0.019]		[0.02]	[0.03]
(initial) Bachelor's degree or higher × t_{77-87}				0.18	0.51***	0.50***
				[0.16]	[0.16]	[0.15]
(initial) Bachelor's degree or higher × t_{87-97}				0.06**	0.07**	0.06
				[0.02]	[0.03]	[0.04]
(initial) Bachelor's degree or higher × t_{97-07}				0.07***	0.10***	0.09***
				[0.01]	[0.02]	[0.02]
Observations	144	144	144	144	144	144
R^2	0.15	0.28	0.20	0.24	0.44	0.47
Regional fixed effects (8 BEA economic areas)	No	No	No	No	No	Yes
Joint significance tests (p-values):						
H_0: Regional FEs = 0	.	.	.	.	.	0.79
H_0: Regional FEs and lightning terms = 0	.	.	.	.	.	0.0065

Pooled OLS estimates. The dependent variable is the yearly growth rate of GSP per worker over the periods 1977–1987, 1987–1997, and 1997–2007. Lightning is the average number of flashes per year per square kilometer, measured by flash detectors. The different proxies for human capital are described in the online appendix and measured at the beginning of each ten-year period (1977, 1987, and 1997), except for enrollment rates (measured in 1980 instead of 1977 for the first period) and the percent of population with a high school diploma or higher (measured in 1980, 1990, and 2000 instead of 1977, 1987, and 1997 for each respective period), due to data availability. The set of regional fixed effects in column 6 accounts for the eight BEA economic areas. All regressions include a constant and a full set of time dummies. Robust standard errors in brackets, adjusted for clustering at the state level. Significant at the ***1%, **5%, and *10% level.

a major way by nearly doubling the standard errors. This is no surprise in light of the strong degree of multicollinearity between the regional effects and lightning intensity. This interpretation is further supported by the fact that while neither lightning nor the set of fixed effects is significant separately, they are jointly significant. In order to examine whether regional effects are at the root of the lightning-growth correlation, we therefore also ran regressions where we add each of the regional fixed effects one by one to the specification in column 5 of table 4. The results are found in the online appendix (table A.3). The key result is that no single BEA region can render lightning imprecise enough to be rejected as statistically insignificant.

In sum, the time-varying effect of lightning on growth is not produced by the growth performance of any particular region and is robust to the inclusion of human capital and time dummies. The specification in column 5 of table 4 will serve as our baseline when we examine the robustness of the lightning-growth link in much greater detail.

Before addressing robustness in depth, however, it is worth commenting on the economic significance of lightning. Taken at face value, the point estimate for the 1990s implies that a 1 standard deviation increase in lightning intensity (about 2.4 flashes per year per sq kilometer) induces a reduction in growth by about 0.2 percentage points ($\approx 0.2 \times \log(2.4)$), conditional on the level of initial labor productivity, human capital, and time effects. This is about 12.5% of the gap between the 5th percentile and the 95th percentile in the distribution of GSP per worker growth rates for the period 1977 to 2007 (for the 48 states in our sample). By extension, variation in lightning by 4 standard deviations (roughly equivalent to moving from the 5th percentile to the 95th percentile in the lightning distribution across U.S. states) can account for about 50% of the "95/5" growth gap.[13] This is a substantial effect.

III. Robustness of the Lightning-Growth Nexus

A. *Climate Shocks*

At first glance, a reasonable objection to the lightning-growth correlation is that it is somehow spurious: perhaps other climate-related variables exert an impact on growth and at the same time happen to be correlated with the flash density.

To be sure, lightning correlates with various kinds of weather phenomena that arise in the context of thunderstorms. Aside from lightning, thunderstorms produce tornadoes, high winds, heavy rainfall, and hailstorms. It seems plausible that these climate variables can induce changes in the growth rate in individual states in their own right. Each of them destroys property (physical capital), people (human capital), or both (Kunkel, Pielke, & Changnon, 1999). By directly affecting the capital-labor ratio, the consequence of, say, a tornado could be changes in growth attributable to transitional dynamics. The nature of the transitional dynamics (i.e., whether growth rises or falls) is unclear as it may depend on whether the tornado destroys more physical or human capital (Barro & Sala-i-Martin, 1995).[14] Nevertheless, since the lightning-growth correlation pertains to a relatively short time span (so far), it is hard to rule out that this reasoning could account for it.

In addition, lightning correlates with temperature: hotter environments usually feature a higher flash density. Temperature has been documented to correlate with economic activity within countries (Nordhaus, 2006; Dell, Jones, & Olken, 2009); therefore, we cannot rule out a priori that the link between lightning and growth is attributable to the intervening influence of temperature.[15]

Hence, in an effort to examine whether climate shocks could account for the lightning-growth correlation, we gathered data on all of the above weather phenomena: temperature, precipitation, tornadoes, hail size, and wind speed. In addition, we obtained data on topography (i.e., elevation) and latitude. The latter is a useful catch-all measure of climate. For good measure, we also obtained data on sunshine, humidity, and cloud cover (albeit it is not entirely clear why these weather phenomena should matter to growth). In total, we have data on ten alternative climate and geography variables (the details on the data are found in the online appendix).

With these data in hand, we ask two questions. First, ignoring lightning, do any of these weather phenomena exhibit a correlation with growth similar to that of lightning? That is, do any of them appear to become more strongly correlated with growth during the period 1977–2007? Second, taking lightning into account, do any of these variables render lightning insignificant?

Tables 5 and 6 report the answers. Columns 2 to 11 of table 5 examine the potentially time-varying impact from each weather variable; column 1 reproduces the lightning regularity from section IIA. It is plain to see that none of the weather variables exhibits a similar growth correlation as that involving lightning. The only variable that influences growth in a statistically significant way in the final period is hail size; however, unlike lightning, hail size also had a statistically significant growth impact in the first period.

In columns 2 to 11 of table 6 we simultaneously include lightning and the various alternative climate and geography controls. In all cases, lightning remains significantly correlated with growth. In fact, when comparing the point estimate for lightning with or without (column 1) additional controls, it emerges that the point estimate is virtually unaffected.

In sum, these results suggest that the lightning-growth correlation is unlikely to be attributable to other weather phenomena.

B. *Institutions and Integration*

An extensive literature examines the impact from historical factors on long-run development. For instance, variation in colonial strategies seems to have an important impact on institutional developments around the world, thus affecting comparative economic development (Acemoglu, Johnson, & Robinson, 2001). Similarly, initial relative factor endow-

---

[13] Log normality of lightning is not accurate—but not terribly misleading either. It does exaggerate the actual variation in lightning slightly; the observed variation is about seven flashes compared to the back-of-the-envelope calculation implying roughly nine.

[14] In a U.S. context, one may suspect a relatively larger impact on physical capital compared to human capital: If so, climate shocks would tend to instigate a growth acceleration in their aftermath, as a higher marginal product of capital induces firms to invest in physical capital.

[15] Nordhaus (2006) and Dell et al. (2009) document a correlation between temperature and income levels, not growth. In fact, Dell et al. (2008), using cross-country data, find that temperature is not correlated with growth in rich places. Nevertheless, the link seems worth exploring.

Table 5.—Growth Regressions with Lightning and Other Geographical and Climate Variables

Dependent Variable	Average Annual Growth in GSP per Worker over Periods of Ten Years (1977–1987, 1987–1997, 1997–2007)										
GEOGRAPHY		Temperature (C degrees)	Precipitation (cm/year)	Tornado Intensity (average EF-scale)	Hail Size (cm)	Wind Speed (km/h)	Humidity (% moisture in air)	Cloudiness (days/year)	Sunshine (days/year)	Elevation (meters above sea level)	Latitude (degrees)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(log, initial) Real GSP per worker	−1.80***	−1.71***	−1.82***	−1.83***	−2.01***	−1.83***	−1.76***	−1.73***	−1.93***	−1.81***	−1.72***
	[0.41]	[0.39]	[0.45]	[0.45]	[0.42]	[0.44]	[0.42]	[0.41]	[0.47]	[0.43]	[0.40]
(log) Lightning × $t_{77–87}$	−0.12										
	[0.11]										
(log) Lightning × $t_{87–97}$	−0.12										
	[0.08]										
(log) Lightning × $t_{97–07}$	−0.21**										
	[0.08]										
(log) GEOGRAPHY × $t_{77–87}$		−0.38	0.77*	1.11*	−1.36**	−0.41*	1.08	0.76	−0.91	−0.31**	1.07
		[0.26]	[0.41]	[0.60]	[0.66]	[0.20]	[1.05]	[0.50]	[0.67]	[0.13]	[0.93]
(log) GEOGRAPHY × $t_{87–97}$		0.31	0.14	0.082	−0.086	0.063	−1.06	−0.25	0.028	0.13	−0.34
		[0.29]	[0.39]	[0.48]	[0.71]	[0.11]	[0.88]	[0.42]	[0.50]	[0.093]	[0.99]
(log) GEOGRAPHY × $t_{97–07}$		−0.033	0.042	−0.25	−1.79*	0.32	−0.38	−0.11	−0.09	0.13	0.95
		[0.35]	[0.19]	[0.22]	[0.95]	[0.32]	[0.59]	[0.34]	[0.48]	[0.087]	[0.80]
Observations	144	144	144	144	144	144	144	144	141	144	144
R^2	0.44	0.42	0.43	0.43	0.44	0.43	0.42	0.42	0.42	0.46	0.42
Human capital controls (enrollment, high school or higher, B.A.)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Pooled OLS estimates. The dependent variable is the annual growth rate in GSP per worker over the periods 1977–1987, 1987–1997, and 1997–2007. All regressions include a constant and a full set of time dummies. Lightning is the average number of flashes per year per square kilometer, measured by flash detectors. The controls for human capital are the initial enrollment rate, percentage of population with a high school diploma or higher, and percentage of population with a B.A. degree. All the human capital controls are measured at the beginning of each ten-year period (1977, 1987, and 1997), except for enrollment rates (measured in 1980 instead of 1977) and the percentage of population with a high school diploma or higher (measured in 1980, 1990, and 2000 instead of 1977, 1987, and 1997, due to data availability). All geographic and climate variables are averages taken over periods of ten years. Robust standard errors in brackets, adjusted for clustering at the state level. Significant at the ***1%, **5%, and *10% levels.

Table 6.—Growth Regressions with Lightning and Geographical and Climate Controls

Dependent Variable	Average Annual Growth in GSP per Worker over Periods of Ten Years (1977–1987, 1987–1997, 1997–2007)										
GEOGRAPHY		Temperature (C degrees)	Precipitation (cm/year)	Tornado Intensity (average EF-scale)	Hail Size (cm)	Wind Speed (km/h)	Humidity (% moisture in air)	Cloudiness (days/year)	Sunshine (days/year)	Elevation (meters above sea level)	Latitude (degrees)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(log, initial) Real GSP per worker	−1.80***	−1.80***	−1.85***	−1.85***	−1.96***	−1.84***	−1.78***	−1.77***	−1.98***	−1.86***	−1.81***
	[0.41]	[0.37]	[0.44]	[0.42]	[0.43]	[0.42]	[0.41]	[0.39]	[0.44]	[0.41]	[0.38]
(log) Lightning × $t_{77–87}$	−0.12	−0.085	−0.07	−0.13	−0.048	−0.19	−0.12	−0.059	−0.07	−0.16	−0.07
	[0.11]	[0.11]	[0.11]	[0.11]	[0.11]	[0.12]	[0.11]	[0.12]	[0.11]	[0.11]	[0.13]
(log) Lightning × $t_{87–97}$	−0.12	−0.16*	−0.11	−0.12	−0.13	−0.11	−0.11	−0.15	0.14	−0.098	−0.20*
	[0.08]	[0.096]	[0.085]	[0.084]	[0.085]	[0.086]	[0.089]	[0.10]	[0.095]	[0.084]	[0.12]
(log) Lightning × $t_{97–07}$	−0.21**	−0.24***	−0.21**	−0.20**	−0.20**	−0.20**	−0.21**	−0.21***	−0.22***	−0.19**	−0.23**
	[0.08]	[0.078]	[0.079]	[0.079]	[0.086]	[0.083]	[0.084]	[0.077]	[0.077]	[0.081]	[0.095]
(log) GEOGRAPHY × $t_{77–87}$		−0.31	0.73*	1.14*	−1.24*	−0.49**	1.01	0.67	−0.76	−0.34***	0.76
		[0.28]	[0.39]	[0.61]	[0.69]	[0.20]	[1.06]	[0.51]	[0.66]	[0.11]	[1.05]
(log) GEOGRAPHY × $t_{87–97}$		0.44	0.10	0.17	0.23	0.055	−1.00	−0.42	0.28	0.11	−1.26
		[0.28]	[0.39]	[0.51]	[0.75]	[0.11]	[0.84]	[0.46]	[0.52]	[0.097]	[1.22]
(log) GEOGRAPHY × $t_{97–07}$		0.30	0.06	−0.13	−0.28	0.16	0.0031	−0.23	0.15	0.065	−0.43
		[0.39]	[0.19]	[0.21]	[0.81]	[0.29]	[0.73]	[0.28]	[0.36]	[0.082]	[0.95]
Observations	144	144	144	144	144	144	144	144	141	144	144
R^2	0.44	0.46	0.47	0.47	0.46	0.47	0.45	0.46	0.46	0.49	0.45
Human capital controls (enrollment, high school or higher, B.A.)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Pooled OLS estimates. The dependent variable is the annual growth rate in GSP per worker over the periods 1977–1987, 1987–1997, and 1997–2007. All regressions include a constant and a full set of time dummies. Lightning is the average number of flashes per year per square kilometer, measured by flash detectors. The controls for human capital are the initial enrollment rate, percentage of population with a high school diploma or higher, and percentage of population with a B.A. degree. All the human capital controls are measured at the beginning of each ten-year period (1977, 1987, and 1997), except for enrollment rates (measured in 1980 instead of 1977), and the percentage of population with a high school diploma or higher (measured in 1980, 1990, and 2000 instead of 1977, 1987, and 1997) due to data availability). All geographic and climate variables are averages taken over periods of ten years. Robust standard errors in brackets, adjusted for clustering at the state level. Significant at the ***1%, **5%, and *10% levels.

ments, determined in large part by climate and soil quality, may well have affected long-run development through inequality and human capital promoting institutions (Engerman & Sokoloff, 2002; Galor, Moav, & Vollrath, 2009). Thus, in many instances, the initial conditions that may have affected long-run developments are related to climate or geography. In the present context, therefore, it seems possible that the lightning-growth correlation may be picking up the influence from such long-run historical determinants of prosperity. Naturally the conventional understanding would be that deep determinants of productivity, (e.g., determinants of political and economic institutions) should have a fairly time-invariant impact on growth. As a result, it would not be surprising if such determinants do not exert a time-varying impact on growth. But whether it is the case is obviously an empirical matter.

To examine whether the lightning-growth nexus is attributable to such effects, we obtained data on ten potential determinants of long-run performance for the United States. The source of the data is Mitchener and McLean (2003), who examine the determinants of long-run productivity levels across U.S. states. In addition, we collected state-level data on three dimensions of global integration, related to international movements of goods and capital. This leaves us with thirteen different potential determinants of labor productivity growth, broadly capturing "institutions, geography and integration" (Rodrik, Subramanian, & Trebbi, 2004).[16]

As in section IIIA, we ask whether these determinants individually exhibit a time-varying impact on growth and whether their inclusion in the growth regression renders lightning insignificant.

In table 7 we examine the impact from various historical determinants of productivity one by one. Of particular note is column 4, the percentage of the population in slavery in 1860. This is the only variable that behaves much like lightning, with a partial correlation that seems stronger at the end of the 1977–2007 period compared to the beginning.

Table 8 includes both lightning and the individual controls. Since the population in slavery is the only variable we have found so far that exhibits a correlation with growth that is qualitatively similar to that of lightning, the results reported in column 4 are of central importance. When both variables enter the growth regression, only lightning retains explanatory power. The point estimate for the last period is more or less unaffected, while the statistical significance of lightning is reduced a bit. But population in slavery does not statistically dominate lightning in the specification. More broadly, it is once again worth observing how stable the partial correlation between lightning and growth seems to be. Comparing the results reported in column 1 (no historical controls) for lightning to those reported in columns 2 to 11, it is clear that the coefficient for lightning is quite robust.

Finally, table 9 examines the potential influence from integration. As seen by inspection of columns 4 and 5, integration proxies cannot account for the lightning-growth correlation either.

The results of this and section, IIIA uniformly/support the same qualitative conclusion: a macroeconomic sensitivity to lightning has emerged over time in the United States. The question is why this is so.

IV. An Explanation for the Lightning-Growth Nexus: IT Diffusion

We begin this section by examining the theoretical foundation behind the claim that lightning (or, more appropriately, the flash density) should have an impact on growth through IT diffusion. Subsequently we examine the hypothesis empirically.

A Theory: Why Lightning Matters to IT Diffusion

The simplest way to think about IT diffusion is by basic neoclassical investment theory. That is, IT diffusion occurs in the context of IT capital investments: higher investments are tantamount to faster IT diffusion.

According to neoclassical investment theory, the central determinant of the desired capital stock, and thus investments for the initial stock given, is the user cost of capital (Hall & Jorgenson, 1967). Two elements of IT user cost are plausibly influenced by lightning: the total price of IT investment goods and the physical rate of IT capital depreciation.

IT capital depreciation is influenced by lightning activity for the following physical reason. Solid-state electronics, such as computer chips, are constructed to deal with commercial power supply in the form of alternating current. The voltage of the current follows a sine wave with a specific frequency and amplitude. If the sine wave changes frequency or amplitude, this constitutes a power disruption. Digital devices convert alternating current to direct current with a much reduced voltage; digital processing of information basically works by having transistors turn this voltage on and off at several gigahertz (Kressel, 2007). If the power supply is disrupted, the conversion process may become corrupted, which causes damage to the equipment, effectively reducing its longevity. It is important to appreciate that even extremely short-lasting power disruptions are potentially problematic. Voltage disturbances measuring less than one cycle (1/60th of a second in the U.S. case) are sufficient to crash or destroy servers, computers, & other microprocessor-based devices (Yeager & Stalhkopf, 2000). A natural phenomenon that damages digital equipment by producing power disruptions is lightning activity (Emanuel & McNeil, 1997; Shim, Qureshi, & Siegel, 2000;

---

[16] See the online appendix for details.

TABLE 7.—GROWTH REGRESSIONS WITH HISTORICAL CONTROLS (GEOGRAPHY AND INSTITUTIONS)

Dependent Variable	Average Annual Growth in GSP per Worker over Periods of Ten Years (1977–1987, 1987–1997, 1997–2007)										
HISTORY		% of Workforce in Mining, 1880	Average Number of Cooling Degree Days	% of 1860 Population in Slavery	Access to Navigable Water	% of 1860 Population on Large Slave Plantations	Settler Origin: English	Settler Origin: French	Settler Origin: Spanish	Settler Origin: Dutch	Average Annual Soldier Mortality in 1829–1838, 1839–1854 (%)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(log, initial) Real GSP per worker	−1.80***	−1.77***	−1.75***	−1.82***	−1.89***	−1.82***	−1.70***	−2.07***	−1.70***	−1.85***	−1.59***
	[0.41]	[0.43]	[0.41]	[0.42]	[0.46]	[0.42]	[0.40]	[0.34]	[0.40]	[0.44]	[0.42]
(log) Lightning × t_{77-87}	−0.12										
	[0.11]										
(log) Lightning × t_{87-97}	−0.12										
	[0.08]										
(log) Lightning × t_{97-07}	−0.21**										
	[0.08]										
HISTORY × t_{77-87}		−0.015*	−0.017*	0.0020	0.49	0.0041	0.49***	−0.33*	−0.45***	0.30	−0.20**
		[0.0082]	[0.0092]	[0.0065]	[0.31]	[0.010]	[0.17]	[0.16]	[0.17]	[0.22]	[0.097]
HISTORY × t_{87-97}		−0.0011	−0.0075	−0.0094	0.23	−0.017**	−0.022	−0.50***	−0.11	0.075	−0.017
		[0.010]	[0.0093]	[0.0058]	[0.31]	[0.0083]	[0.19]	[0.15]	[0.16]	[0.25]	[0.098]
HISTORY × t_{97-07}		0.0078	−0.00097	−0.0097*	0.15	−0.014*	−0.14	−0.18	0.092	0.22	−0.19*
		[0.0061]	[0.011]	[0.0049]	[0.17]	[0.0071]	[0.17]	[0.13]	[0.15]	[0.29]	[0.10]
Observations	144	144	144	144	144	144	144	144	144	144	144
R^2	0.44	0.42	0.42	0.43	0.43	0.43	0.45	0.46	0.44	0.41	0.43
Human capital controls (enrollment, high school or higher, BA.)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Pooled OLS estimates. The dependent variable is the annual growth rate of GSP per worker over the periods 1977–1987, 1987–1997, and 1997–2007. All regressions include a constant and a full set of time dummies. Lightning is the average number of flashes per year per square kilometer, measured by flash detectors. The controls for human capital are the initial enrollment rate, percentage of population with a high school diploma or higher, and percentage of population with a B.A. degree. All the human capital controls are measured at the beginning of each ten-year period (1977, 1987, and 1997), except for enrollment rates (measured in 1980 instead of 1977) and the percentage of population with a high school diploma or higher (measured in 1980, 1990, and 2000 instead of 1977, 1987, and 1997) due to data availability. HISTORY controls taken from Mitchener and McLean (2004). Robust standard errors in brackets, adjusted for clustering at the state level. Significant at the ***1%, **5%, and *10% levels.

TABLE 8.—GROWTH REGRESSIONS WITH LIGHTNING AND HISTORICAL CONTROLS (GEOGRAPHY AND INSTITUTIONS)

Dependent Variable:	Average Annual Growth in GSP per Worker over Periods of Ten Years (1977–1987, 1987–1997, 1997–2007)										
HISTORY		% of Workforce in Mining, 1880	Average Number of Cooling Degree Days	% of 1860 Population in Slavery	Access to Navigable Water	% of 1860 Population on Large Slave Plantations	Settler Origin: English	Settler Origin: French	Settler Origin: Spanish	Settler Origin: Dutch	Average Annual Soldier Mortality in 1829–1838, 1839–1854 (%)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(log, initial) Real GSP per worker	−1.80***	−1.80***	−1.76***	−1.80***	−1.92***	−1.79***	−1.73***	−2.03***	−1.73***	−1.86***	−1.65***
	[0.41]	[0.42]	[0.40]	[0.41]	[0.44]	[0.41]	[0.39]	[0.35]	[0.39]	[0.42]	[0.40]
(log) Lightning × t_{77-87}	−0.12	−0.14	−0.051	−0.14	−0.10	−0.14	−0.098	−0.072	−0.10	−0.11	−0.087
	[0.11]	[0.12]	[0.12]	[0.12]	[0.12]	[0.12]	[0.10]	[0.12]	[0.10]	[0.11]	[0.11]
(log) Lightning × t_{87-97}	−0.12	−0.12	−0.11	−0.072	−0.12	−0.067	−0.12	−0.047	−0.11	−0.12	−0.12
	[0.08]	[0.083]	[0.092]	[0.10]	[0.086]	[0.100]	[0.085]	[0.11]	[0.084]	[0.083]	[0.089]
(log) Lightning × t_{97-07}	−0.21**	−0.20**	−0.28***	−0.18*	−0.22***	−0.19**	−0.20***	−0.20**	−0.20**	−0.21**	−0.18**
	[0.08]	[0.089]	[0.079]	[0.092]	[0.079]	[0.089]	[0.076]	[0.092]	[0.077]	[0.080]	[0.088]
HISTORY × t_{77-87}		−0.016**	−0.015	0.0042	0.47	0.0068	0.48***	−0.29	−0.44**	0.28	−0.18*
		[0.0079]	[0.0098]	[0.0075]	[0.30]	[0.011]	[0.17]	[0.20]	[0.17]	[0.23]	[0.097]
HISTORY × t_{87-97}		−0.0035	−0.0017	−0.0076	0.23	−0.015	−0.022	−0.48***	−0.10	0.037	0.016
		[0.010]	[0.0092]	[0.0070]	[0.31]	[0.0096]	[0.19]	[0.18]	[0.16]	[0.25]	[0.10]
HISTORY × t_{97-07}		0.0015	0.017***	−0.0044	0.21	−0.0065	−0.10	−0.055	0.065	0.19	−0.12
		[0.0065]	[0.0058]	[0.0056]	[0.17]	[0.0079]	[0.14]	[0.15]	[0.13]	[0.27]	[0.12]
Observations	144	144	144	144	144	144	144	144	144	144	144
R^2	0.44	0.46	0.46	0.45	0.47	0.46	0.48	0.48	0.48	0.45	0.46
Human capital controls (enrollment, high school or higher, B.A.)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Pooled OLS estimates. The dependent variable is the annual growth rate of GSP per worker over the periods 1977–1987, 1987–1997, and 1997–2007. All regressions include a constant and a full set of time dummies. Lightning is the average number of flashes per year per square kilometer, measured by flash detectors. The controls for human capital are the initial enrollment rate, percentage of population with a high school diploma or higher, and percentage of population with a B.A. degree. All the human capital controls are measured at the beginning of each 10-year period (1977, 1987, and 1997), except for enrollment rates (measured in 1980 instead of 1977) and the percentage of population with a high school diploma or higher (measured in 1980, 1990, and 2000 instead of 1977, 1987, and 1997), due to data availability. HISTORY controls taken from Mitchener and McLean (2004). Robust standard errors in brackets, adjusted for clustering at the state level. Significant at the ***1%, **5%, and *10% levels.

Table 9.—Growth Regressions with Lightning and Trade and Integration Controls

Dependent Variable	Average Annual Growth in GSP per Worker over Periods of Ten Years (1977–1987, 1987–1997, 1997–2007)				
INTEGRATION		Agricultural Exports per Capita	FDI per Capita	Agricultural Exports per Capita	FDI per Capita
	(1)	(2)	(3)	(4)	(5)
(log, initial) Real GSP per worker	−1.80***	−1.81***	−1.78***	−1.82***	−1.79***
	[0.41]	[0.38]	[0.51]	[0.38]	[0.50]
(log) Lightning × t_{77-87}	−0.12			−0.023	−0.12
	[0.11]			[0.11]	[0.11]
(log) Lightning × t_{87-97}	−0.12			−0.082	−0.12
	[0.08]			[0.088]	[0.085]
(log) Lightning × t_{97-07}	−0.21**			−0.24***	−0.21***
	[0.08]			[0.067]	[0.077]
(log) INTEGRATION × t_{77-87}		−0.13**	0.023	−0.13**	0.034
		[0.048]	[0.15]	[0.051]	[0.15]
(log) INTEGRATION × t_{87-97}		−0.094	0.11	−0.08	0.11
		[0.057]	[0.18]	[0.063]	[0.17]
(log) INTEGRATION × t_{97-07}		0.065	−0.17	0.10**	−0.19
		[0.040]	[0.13]	[0.039]	[0.13]
Observations	144	144	144	144	144
R^2	0.44	0.46	0.41	0.49	0.45
Human capital controls (enrollment, high school or higher, B.A.)	Yes	Yes	Yes	Yes	Yes

Pooled OLS estimates. The dependent variable is the annual growth rate of GSP per worker over the periods 1977–1987, 1987–1997, and 1997–2007. All regressions include a constant and a full set of time dummies. Lightning is the average number of flashes per year per square kilomater, measured by flash detectors. The controls for human capital are the initial enrollment rate, percentage of population with a high school diploma or higher, and percentage of population with a B.A. degree. All the human capital controls are measured at the beginning of each ten-year period (1977, 1987, and 1997), except for enrollment rates (measured in 1980 instead of 1977) and the percentage of population with a high school diploma or higher (measured in 1980, 1990, and 2000 instead of 1977, 1987, and 1997), due to data availability. Robust standard errors in brackets, adjusted for clustering at the state level. Significant at the ***1%, **5%, and *10% levels.

Chisholm, 2000).[17] This avenue of influence is a priori highly plausible. In the United States lightning produces a large fraction of the total number of power disruptions (Chisholm & Cummins, 2006); firms specializing in delivering power protection are another testimony to the same thing.

The latter point immediately raises the issue that firms can take preemptive actions so as to reduce the impact of lightning on the cost of capital, say, by investing in surge protectors. However, the crux of the matter is that this imposes an additional cost to be carried in the context of IT investments; it amounts to an increasing IT investment price. Hence, even if we take the likely preemptive measures into account, more lightning-prone areas will face higher IT user costs.

In sum, in areas with a greater flash density, the speed of IT diffusion, as measured by IT capital accumulation, will proceed at a slower pace. The reason is that a higher lightning density increases the frequency of power disturbances, IT capital depreciation (or the price of IT investments), and the user cost of IT capital, and thus lowers IT investments. Moreover, if output is increasing in the IT capital stock, growth in output will similarly tend to be slower in areas with greater lightning activity, conditional on the initial level of output.

While these theoretical considerations speak to a direct impact of lightning on IT investment, there could be an important complementary mechanism at work. The choice of firm location may depend on the quality of power supply, and thus lightning. Specifically, it may be the case that IT-intensive firms choose to locate in areas where lightning intensity is modest, due to the resulting (slightly) higher power quality. Interestingly, the National Energy Technology Laboratory (2003), operated by the U.S. Department of Energy, reports that a recent firm-level survey had 34% respondents saying that they would shift business operations out of their state if they experienced ten or more unanticipated power disturbances over a quarter of a year.[18] Hence, it seems plausible that this mechanism also could affect comparative IT penetration across U.S. states.

To this, one may add that in areas with frequent power disruptions and outages, the marginal benefit of owning a computer is probably lowered as well. Obviously if consumers and firms face regular power outages, it will be difficult to employ IT efficiently. But even if power disruptions are infrequent and brief, power disruptions lead to glitches and downtime, which serves to lower the productivity of IT

---

[17] Note that lightning may enter a firm or household in four principal ways. First, lightning can strike the network of power, phone, and cable television wiring. This network, particularly when elevated, acts as an effective collector of lightning surges. The wiring conducts the surges directly into the residence and then to the connected equipment. In fact, the initial lightning impulse is so strong that equipment connected to cables up to 2 kilometers away from the site of the strike can be damaged (Bundesamt für Sicherheit, 2004). Second, when lightning strikes directly to or nearby air conditioners, satellite dishes, exterior lights, and so on, the wiring of these devices can carry surges into the residence. Third, lightning may strike nearby objects such as trees, flagpoles, and road signs, which are not directly connected to the residence. When this happens, the lightning strike radiates a strong electromagnetic field, which can be picked up by the wiring in the building, producing large voltages that can damage equipment. Finally, lightning can strike directly into the structure of the building. This type of strike is extremely rare, even in areas with a high lightning density.

[18] The report is available at: http://www.netl.doe.gov/moderngrid/.

equipment. Hence, aside from increasing the marginal costs of IT capital, lightning may also work to lower IT productivity.

Schematically we may summarize the theoretical considerations above in the following way:

$$\text{Lightning density} \rightarrow \text{Power disturbances} \rightarrow \text{IT investments} \rightarrow \text{Growth,}$$

where the second-from-last arrow subsumes the likely impact from (lightning-induced) power disturbances on IT costs and benefits.

The mechanisms linking lightning to growth are likely to have become increasingly important over time for a number of reasons. First, IT capital investments accounted for a substantial part of output growth, starting in the 1990s (Jorgenson, 2001). Consequently, factors that have an impact on IT capital accumulation (e.g., the flash density) should also become more important to growth. Second, the 1990s was the era during which the Internet emerged (in the sense of the World Wide Web), a conceivable reason that firms chose to intensify IT investments during the same period.[19] From a physical perspective, however, the network connection is another way in which lightning strikes may reach the computer, in the absence of wireless networks (which have not been widespread until very recently). Third, the 1990s saw rapid increases in the computing power of IT equipment. In keeping with Moore's law, processing speed doubled roughly every other year. This is an important propagation mechanism of the lightning-IT investment link. The reason is that the sensitivity of computers to small power distortions increases with the miniaturization of transistors, which is the key to increasing speed in microprocessors (Kressel, 2007).[20] As a result, these factors would all contribute to increasing the importance of the flash density to IT investments, and thus to growth, during the 1990s. Whether this theory is relevant is an empirical issue, to which we now turn.

B. *Empirical Analysis: Lightning, IT Diffusion and Economic Growth*

In order for the above theory to be able to account for "the lightning-growth correlation," two things need be true. First, it must be the case that lightning is a strong predictor of IT across the U.S. states. Second, there should be no explanatory power left in lightning in relation to growth once we control for IT. We examine these two requirements in turn.

In measuring the diffusion of IT capital across the United States, we employ three different measures. Two measures derive from a supplement to the 2003 Current Population Survey, which contained questions about computer and Internet use; the third measure derives from the 2007 Economic Census (see the online appendix for further detail). The first measure is the percentage of households with access to the Internet; the second is the percentage of households with a PC; and the third is manufacturing firms' capital expenditures on computers and related equipment as a percentage of total capital expenditures on machinery and equipment.[21] A few comments on the IT data are in order.

First, our IT measures allow us to explore IT penetration in the U.S. economy from two perspectives: the firm and the household side. Whereas the household data speak exclusively to the level of IT investments, the firm data arguably speaks to both IT investments and location choice. In the end, there are two reasons that the fraction of IT expenditures to total capital expenditure might be higher in some states compared to others. On the one hand, there is the investment effect, which captures that structurally similar manufacturing firms have different levels of IT investments, depending on whether they locate in high- versus low-lightning-density areas; this sort of information is also likely captured by our household data. However, there is a potential composition effect which captures that areas with less lightning may attract more IT-intensive firms, which drives up the IT expenditure/total capital expenditure ratio. Both effects, which we admittedly cannot disentangle, would predict a negative relationship between lightning density and manufacturing IT investment intensity.

Second, one may worry about vintage capital effects. In a vintage growth setting, a higher (lightning-induced) rate of capital depreciation will in principle have two opposite effects on the IT capital stock. One the one hand, we expect lower overall investments. On the other hand, faster depreciation implies that more recent (more productive) vintages take up a larger share of the stock. As a result, one may worry about the net impact of lightning on IT capital and long-run productivity. Unfortunately we do not have access to information about IT quality, which would be ideal. Still,

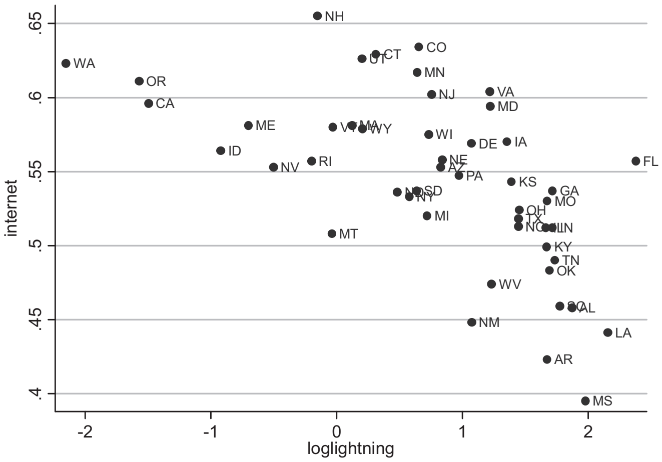
---

[19] The WWW was launched in 1991 by CERN (the European Organisation for Nuclear Research). See Hobbes' Internet Timeline v8.2 http://www.zakon.org/robert/internet/timeline/.

[20] This is well known in the business world: "The spread of technology has spawned a need for lightning-security specialists. 'The computer chip, the smaller it's gotten, the more susceptible it is,' says Mark Harger, owner of Harger Lightning and Grounding in Grayslake, Ill. 'It's been a boon to our business.' His company manufactures systems that shield buildings from direct strikes and power surges from nearby lightning. With a steady stream of orders from financial and technology companies looking to protect their data centers, the company has gone from eight employees to 100 over the past twenty years." "There Go the Servers: Lightning's New Perils," *Wall Street Journal*, August 25, 2009.

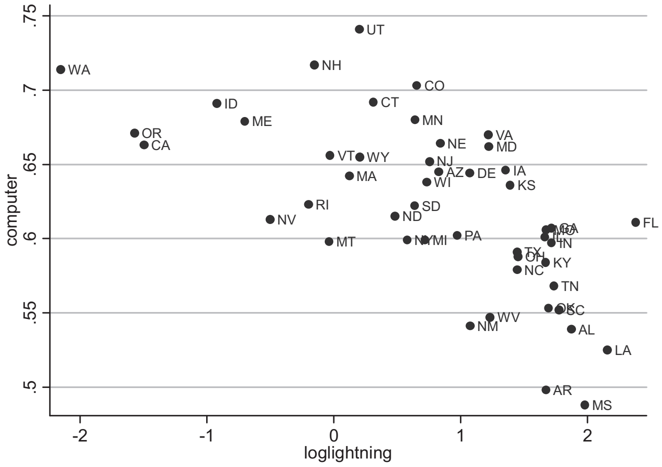
[21] We did consider inferring IT capital intensity at the state level since the BEA produces sector-specific data on IT capital stocks. To exploit these data, we would have to assume that the marginal product of IT capital is equalized within sectors, across states. Weighting the sector-specific IT capital intensities by state-specific sector composition would yield a guesstimate for state IT capital intensity. However, since (state-specific) lightning affects the user cost of capital via the price of acquisition or the rate of capital depreciation, the assumption of within-industry equalization of marginal products is implausible on a priori grounds. To put it differently, the main avenue through which lightning should affect IT capital intensity would be eliminated by construction had we used this procedure to generate state-level IT capital. As a result, we have not pursued the matter further.

FIGURE 7.—LIGHTNING VERSUS INTERNET USERS PER 100 HOUSEHOLDS, 2003



The raw correlation between the two series is −0.62. See the online appendix.

FIGURE 8.—LIGHTNING VERSUS PERSONAL COMPUTERS PER 100 HOUSEHOLDS, 2003

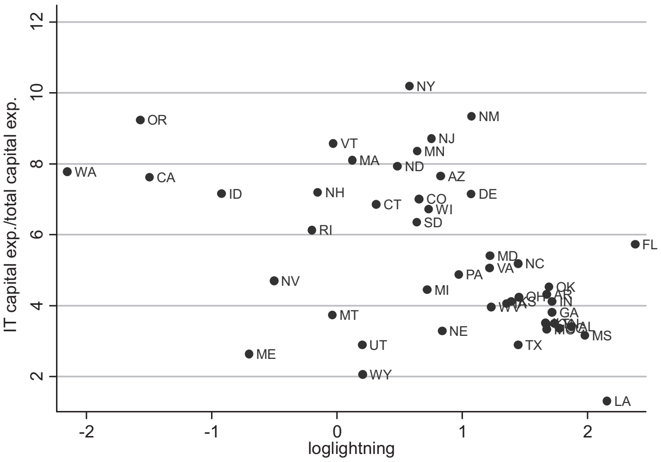


The raw correlation between the two series is −0.65. See the online appendix.

on a priori grounds, a higher rate of capital depreciation unambiguously lowers IT capital intensity in the standard neoclassical vintage growth model (Phelps, 1962). Hence, even allowing for vintage effects, higher depreciation should lower IT intensity and thereby long-run productivity. Moreover, if the IT variable is measured with gross error, it would tend to make it less likely that it appears as a significant growth determinant in the regressions to follow at the end of this section; that is, it would make it less likely that IT (as measured here) can account for the lightning-growth correlation.[22]

Third, with only one observation for the IT variables, we have to settle for cross-section regressions.

FIGURE 9.—LIGHTNING VERSUS MANUFACTURING FIRMS' ICT CAPITAL EXPENDITURE TO TOTAL CAPITAL EXPENDITURE



The raw correlation between the two series is −0.49. See the online appendix.

Finally, one may question whether there is value in using both household IT variables, since having access to a computer is a prerequisite for the use of the Internet. Yet, the emergence of the Web is a much more recent technology than the PC, which dates to 1991 and started spreading earlier. Hence, the initial conditions that may matter to the speed of adoption are discernible by time. For instance, whereas educational attainment in the 1970s should influence the spread of the personal computer, the Internet is affected by education levels in the 1990s. Consequently, the two empirical models of IT diffusion will have to differ in terms of the dating of the right-hand-side IT diffusion determinants. As a result, we employ both.

A natural point of departure is the simple correlation between the flash density and the three IT measures for the 48 states in our sample. Figures 7 to 9 depict them. Visually, the strong negative correlations between the flash density and household and firm IT use, respectively, are unmistakable. By the middle of the first decade of the twenty-first century, states that experienced lightning strikes at a higher frequency also had relatively fewer users of computers and the Internet, as well as lower IT investment intensity in manufacturing.

A more systematic approach involves more controls. Human capital is probably the first additional determinant of diffusion that comes to mind. The idea that a more educated labor force is able to adopt new technologies more rapidly is an old one, going back at least to the work of Nelson and Phelps (1966). Another natural control is the level of GSP per worker. Aside from being a catch-all control for factors that facilitate diffusion, it can also be motivated as a measure of the "distance to the frontier." The sign of the coefficient assigned to GSP per worker is therefore ambiguous. A positive sign is expected if initially richer areas are able to acquire IT equipment more readily. A negative sign could arise if richer areas, by closer proximity to the technology frontier, are less able to capitalize on "advantages of backwardness."

---

[22] If IT is poorly measured, this would also make it less likely that we can establish a link between lightning and IT. Measurement error (in this case) is found in the dependent variable, for which reason it will (under standard assumptions) inflate the standard errors of the estimated parameters. It thus becomes less likely to observe a statistically significant correlation with lightning activity.

In addition to labor productivity and human capital, we chiefly follow Caselli and Coleman (2001) in choosing relevant additional determinants of IT diffusion (they also include human capital and income per capita). First, we use measures for the composition of production; it seems plausible that IT may spread more rapidly in areas featuring manufacturing rather than agriculture. Second, we employ proxies for global links, measured by international movements of goods and capital, and a measure of local market size: state population. Third, we employ various historical variables as controls. Caselli and Coleman, studying cross-country data, include a measure of economic institutions, which we are not able to do directly in our U.S. sample. However, by including various plausible historical determinants of productivity (e.g., soldier mortality, the pervasiveness of slavery in the late nineteenth century), we hope to pick up much the same type of information. Of course, in U.S. cross-state data, one expects differences in institutional quality to be a great deal smaller than what is typically found in cross-country data. Finally, moving beyond the "Caselli-Coleman controls," we examine the impact from the age structure of the population, religiousness, ethnic composition, and urbanization on IT diffusion.[23]

In table 10 we report baseline results for all three IT measures. In columns 1, 5, and 9 of the table, we examine the simple correlations between the flash density and computer use, Internet use, and manufacturing firms' IT investments, respectively. The lightning variable is always highly significant and accounts for about 24% to 43% of the variation in the IT variables. In the remaining columns, we add human capital controls and regional fixed effects progressively. Lightning is always highly significant, even with the inclusion of eight regional fixed effects. The only other variable that is consistently significant is the fraction of state population with a B.A. degree or higher; this is consistent with previous findings (Caselli & Coleman, 2001; Beaudry et al., 2006). It is also worth noting that we are able to span more than 80% of the variation in IT on the household side (columns 4 and 8) and more than 60% on the firm side (column 12).

Using the estimate from column 7 in table 10 we find that a 1 standard deviation increase in lightning leads to a reduction in Internet users by about 1 percentage point.[24] In 2003 the states with the lowest Internet penetration (the fifth percentile) had about 44% of the population able to access the Internet; at the other end of the spectrum (the 95th percentile), about 60% of the population was online. Hence the estimate for lightning implies that 1 standard deviation change in lightning can account for about 6% of the 95/5 gap; 4 standard deviations therefore motivates about 25% of the difference.

In an effort to check for robustness, table 11 introduces additional controls to the long regressions in table 10 (col-

TABLE 10.—LIGHTNING AND IT DIFFUSION

Dependent Variable	% of Households with a personal Computer at Home, 2003				% of Households with Internet Access at Home, 2003				Manufacturing Firms' IT Investments, 2007			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
(log) Lightning	−3.68***	−3.68***	−1.15***	−2.66***	−3.57***	−3.57***	−1.14***	−1.69*	−1.06***	−1.06***	−0.99***	−1.69**
	[0.56]	[0.58]	[0.38]	[0.80]	[0.61]	[0.62]	[0.41]	[0.88]	[0.23]	[0.24]	[0.26]	[0.64]
(log) Real GSP per worker, 1991		5.57*	1.96	4.64		9.95***	4.83	5.32		1.39	−3.31	−4.05*
		[3.26]	[2.85]	[3.19]		[3.46]	[2.97]	[3.70]		[1.92]	[2.00]	[2.37]
Enrollment rate, 1991			0.066	0.037			−0.0054	0.05			−0.20***	−0.17
			[0.097]	[0.20]			[0.092]	[0.22]			[0.066]	[0.14]
High school diploma or higher, 1990			0.60***	0.76***			0.53***	0.77***			−0.091	0.014
			[0.11]	[0.15]			[0.11]	[0.19]			[0.058]	[0.12]
Bachelor's degree or higher, 1991			0.35**	0.30**			0.45***	0.39**			0.32***	0.29**
			[0.15]	[0.13]			[0.15]	[0.17]			[0.073]	[0.14]
Observations	48	48	48	48	48	48	48	48	48	48	48	48
R^2	0.43	0.45	0.79	0.84	0.38	0.45	0.77	0.82	0.24	0.25	0.50	0.63
Regional fixed effects (8 BEA economic areas)	No	No	No	Yes	No	No	No	Yes	No	No	No	Yes
H_0: Regional FEs = 0 (p value)	.	.	.	0.02	.	.	.	0.28	.	.	.	0.09

OLS estimates. The dependent variables are (a) the percentage of household with access to a personal computer at home in 2003, (b) the percentage of households with access to Internet at home, and (c) the level of IT investments in the manufacturing sector, measured as the amount of capital expenditure on computers and peripheral data processing equipment, relative to all nonconstruction capital expenditures, respectively. Lightning is the average number of flashes per year per square kilometer, measured by flash detectors. The rest of the covariates are described in the online appendix. Significant at the ***1%, **5%, and *10% levels.

---

[23] Details on all the data mentioned above are given in the online appendix.

[24] Recall that the standard deviation of the flash density variable is 2.4 in our 48-state sample.

Table 11.—Lightning and IT Diffusion: Additional Controls

Additional Control		Economy Structure			Trade and Integration			Institutions			Religion	Race and Ethnicity			Urbanization	Age Structure	
		Share of Agri-culture in GSP, 1991	Share of Government in GSP, 1991	Share of Manu-facturing in GSP, 1991	(log) FDI Per Capita, 1991	(log) Agri-cultural Exports per Capita, 1991	(log) Population, 1991	Soldier Mortality, Ages 1829–1854	% of Workforce in Mining, 1880	% of Slavery, 1860	% Population Attending a Church or a Synagogue Almost Every Week, Average. 2004–2006	% White Population, 1990	% Black Population, 1990	% Hispanic Origin Population, 1990	% Urban Population, 1990	% Population Age 15 Years or Less, 1990	% Population Ages 15–64 Years, 1990
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
Dependent Variable	A: Percentage of Households with a Personal Computer at Home, 2003																
(log) Lightning	−2.66***	−3.16***	−2.71***	−2.58***	−2.58***	−2.68***	−2.75***	−3.78***	−2.63***	−2.57***	−2.63***	−2.20**	−2.12**	−2.66***	−3.01***	−2.62***	−2.69***
	[0.80]	[0.92]	[0.84]	[0.84]	[0.79]	[0.82]	[0.80]	[0.80]	[0.77]	[0.86]	[0.84]	[0.89]	[0.91]	[0.83]	[0.83]	[0.87]	[0.86]
Additional Control		−0.35	−0.046	0.13*	−1.07	−0.22	0.83	1.76**	0.03	−0.015	0.073	0.18**	−0.13	−0.036	0.063	0.10	0.10
		[0.27]	[0.20]	[0.075]	[1.35]	[0.51]	[0.52]	[0.65]	[0.060]	[0.054]	[0.27]	[0.074]	[0.082]	[0.090]	[0.052]	[0.39]	[0.44]
R^2	0.84	0.85	0.84	0.85	0.84	0.84	0.85	0.86	0.84	0.84	0.84	0.86	0.85	0.84	0.85	0.84	0.84
Regional fixed effects (8 BEA economic regions)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
H_0: Regional FEs = 0 (p value)	0.02	0.04	0.04	0.02	0.02	0.02	0.01	0.001	0.04	0.03	0.11	0.02	0.01	0.10	0.03	0.02	0.03
Dependent Variable	B: Percentage of Households with Internet Access at Home, 2003																
(log) Lightning	−1.69*	−1.15***	−1.07**	−1.19**	−1.08**	−0.99**	−1.18***	−1.17***	−1.27***	−1.27***	−1.34**	−0.85*	−0.83*	−1.21**	−1.12**	−0.98**	−0.99**
	[0.88]	[0.41]	[0.40]	[0.46]	[0.41]	[0.44]	[0.41]	[0.42]	[0.45]	[0.44]	[0.63]	[0.46]	[0.48]	[0.49]	[0.43]	[0.37]	[0.41]
Additional Control		−0.14	−0.18	0.12	−1.46	−0.36	0.40	0.16	−0.05	0.025	0.15	0.21***	−0.11	−0.14*	−0.031	−0.49	0.41
		[0.19]	[0.23]	[0.084]	[1.64]	[0.37]	[0.39]	[0.53]	[0.043]	[0.050]	[0.29]	[0.060]	[0.080]	[0.070]	[0.039]	[0.34]	[0.33]
R^2	0.82	0.77	0.78	0.78	0.78	0.78	0.77	0.77	0.78	0.77	0.77	0.83	0.78	0.80	0.77	0.79	0.78
Regional fixed effects (8 BEA economic regions)	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
H_0: Regional FEs = 0 (p value)	0.28	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Dependent Variable	C: IT Investments of Manufacturing Firms, 2007																
(log) Lightning	−1.69**	−1.66**	−1.98***	−1.69**	−1.77**	−1.71**	−1.64**	−1.36*	−1.63**	−1.32*	−1.87***	−1.53**	−1.24*	−1.67***	−1.72**	−1.79***	−1.69**
	[0.64]	[0.74]	[0.55]	[0.64]	[0.65]	[0.63]	[0.68]	[0.71]	[0.60]	[0.66]	[0.57]	[0.66]	[0.64]	[0.56]	[0.64]	[0.59]	[0.66]
Additional Control		0.021	−0.28**	−0.011	1.06	−0.21	−0.37	−0.52	0.048*	−0.059***	−0.43***	0.06	−0.10**	0.094**	0.006	−0.27**	0.028
		[0.20]	[0.13]	[0.055]	[0.79]	[0.31]	[0.43]	[0.42]	[0.025]	[0.020]	[0.14]	[0.037]	[0.042]	[0.042]	[0.032]	[0.11]	[0.21]
R^2	0.63	0.63	0.68	0.63	0.65	0.63	0.64	0.64	0.64	0.67	0.70	0.64	0.68	0.67	0.63	0.66	0.63
Regional fixed effects (8 BEA economic regions)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
H_0: Regional FEs = 0 (p value)	0.09	0.10	0.00	0.09	0.05	0.09	0.04	0.06	0.04	0.01	0.01	0.05	0.03	0.09	0.10	0.10	0.10

OLS estimates. All regressions have 48 observations, include a constant term, and control for the levels of (log) real gross state product per worker, enrollment rates, and percentage of population with a high school diploma or higher degree in 1991, and the percentage of population with a B.A. degree in 1990. The dependent variables are (panel A) the percentage of households with access to a personal computer at home in 2003, (panel B) the percentage of households with access to the Internet at home, and (panel C) the level of IT investments in the manufacturing sector, measured as the amount of capital expenditures on computers and peripheral data processing equipment, relative to all nonconstruction capital expenditures, respectively. Lightning is the average number of flashes per year per square kilometer, measured by flash detectors. Robust standard errors in brackets. Significant at the ***1%, **5%, and *10% levels.

umns 4, 8, and 12), one by one. Nowhere is the influence from the flash density eliminated. Rather, the point estimate appears reasonably robust to the inclusion of alternative IT diffusion controls, economically as well as statistically.

The lightning-IT correlation can obviously not be ascribed to reverse causality. Moreover, since the remaining diffusion determinants are lagged, the risk that the endogeneity of these variables is contaminating the OLS estimate for lightning is diminished. To be sure, it is impossible to completely rule out that the partial correlation between lightning and IT could be attributed to one or more omitted variables in the analysis. Still, a causal interpretation is well founded on theoretical grounds: the empirical link between IT and lightning is clearly robust to a reasonable set of alternative IT determinants, and it is robust to regional fixed effects. Moreover, the point estimate seems stable across specifications. These characteristics provide a sound basis for believing the estimates can be taken to imply that lightning is causally affecting the speed of IT diffusion. We can, however, push the matter further on two accounts. First, we can ask whether IT can account for the link between growth and lightning. This is basically an indirect check of the exclusion restrict in an IV setup, where lightning serves as instrument for IT. Second, we can simply perform such an IV exercise.

Table 12 shows the relevant regression results. In columns 1 to 13, we address the first issue; in columns 14 and 15, we address the second issue. Our focus is specifically on the 1991–2007 period, as this is the time during which lightning is significantly correlated with growth.

In column 1 of table 12 the lightning-growth correlation is reproduced. In the following three columns, we add the IT measures. Individually, all three are significantly and positively correlated with growth, as expected. The interpretation of the household IT variables is slightly different, though. The Internet originated in 1991. As a result, the independent variable can be seen as a proxy for Internet investments over the period; in 1991 the number of Internet users inevitably was close to 0, so the 2003 value effectively captures changes in Internet users over the relevant period. The same is not true for computers, which started diffusing far earlier. If the IT investment rate is the relevant control, the computer variable is therefore measured with error. This may account for the fact that the economic size of the impact of the Internet variable is larger than that of computers in table 12.

A key result of the exercise is reported in columns 5 to 7. When the IT variables are added to the equation, the flash density loses significance. The loss of significance is mainly attributable to a much lower point estimate; in column 7, it is reduced by almost a factor of 7. A reasonable interpretation is that lightning appears in the growth regression due to its impact on IT diffusion. In columns 8 to 10, we include all four variables at once; in column 9, all human capital controls are also included, whereas in column 9, regional fixed effects are added to the list. Despite the obvious multicollinearity in this experiment, manufacturing firms' IT investment share remains strongly significant. This means that this latter variable dominates household computer and Internet use as a predictor of U.S. cross-state real GSP growth rates in the Internet era: 1991 onward. This continues to be the case when we exclude lightning, as done in columns 11 to 13.

In columns 14 and 15, we turn to an IV exercise using lightning as an instrument for manufacturing firms' IT investment share. In light of column 7, we have good reason to be optimistic that lightning satisfies the required exclusion restriction. In the IV regressions, we always include the human capital controls; in column 14, we include in addition the eight regional fixed effects.

Turning to the results, we first note that lightning is significant in the first stage in both columns. Moreover, the 2SLS point estimate is very similar to what is found using OLS. As expected, lightning is only a moderately strong instrument when the eight regions are included, as in column 14. However, the weak instrument robust Stock-Wright (2000) S statistic, which tests the null that the coefficient of the endogenous regressor in the second stage is equal to 0, deems the IT variable significant. Moreover, since the regional fixed effects jointly are not even marginally significant, they can safely be excluded, in which case the lightning instrument becomes strong (first stage $F > 10$). Figure 10 provides a visual representation of the IV results.

What is the economic significance of IT diffusion on growth? One approach would be to study the impact effect on growth from an increase in the intensity of IT investments. If we use the estimate from table 12 (column 15), we find that a 1 percentage point increase in IT investment intensity increases growth—on impact—by about 0.15 percentage points. Of course, the initial growth impact should then drop off as the economy converges toward steady state.

Another approach is to study the impact from greater IT investment intensity on the long-run level of GDP per worker rather than IT investments' impact on transitional growth. Taking the IV estimate at face value (again table 12, column 15), we find that an increase in IT expenditures as a fraction of total expenditures by 1% increases long-run labor productivity by about 0.6 percent.[25] Hence, our estimates suggest that IT indeed exerted a positive influence on growth, consistent with previous micro level (firm level) estimates (Brynjolfsson & Hitt, 2003).

Overall, we believe our analysis builds a fairly strong case in favor of the IT diffusion hypothesis that lightning appears as a growth determinant in the 1990s due to the

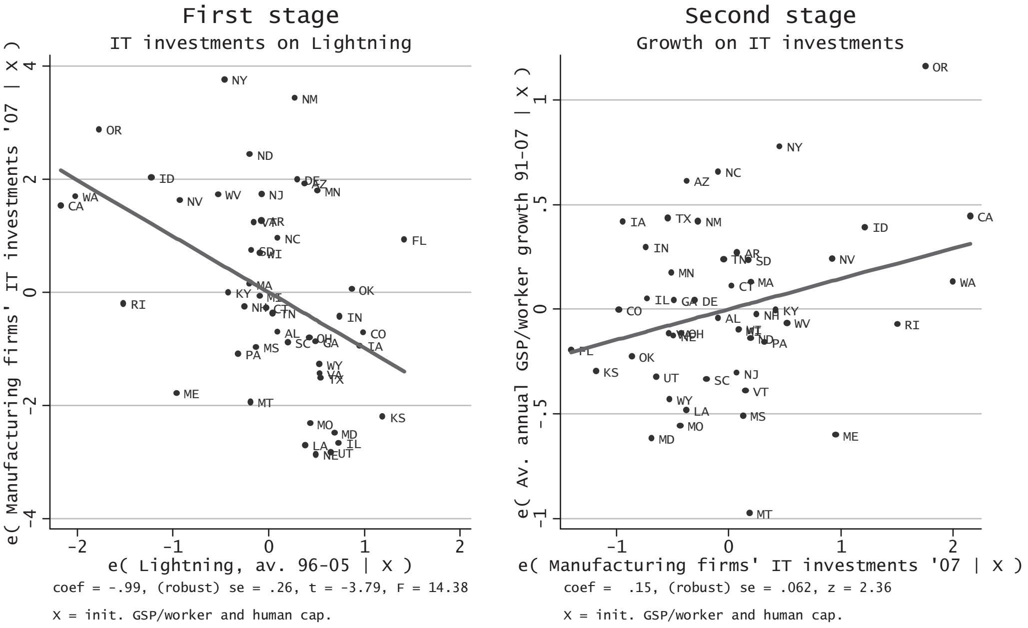
[25] The implicit calculation proceeds as follows. Consider steady state where growth in GDP per worker is 0 (or constant). Then we can work out the semielasticity of steady-state GDP per worker with respect to IT investments as $0.15/1.25 = 0.12$ (table 12, column 15). Evaluated at the mean investment level (see table 2), we then find the elasticity of roughly 0.6 ($= 0.12 \times 5.4$).

TABLE 12.—LIGHTNING, IT DIFFUSION, AND ECONOMIC GROWTH

Dependent Variable:	Average Annual Growth in GSP per Worker, 1991–2007														
	OLS													IV	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
(log) Real GSP per worker, 1991	−0.66	−0.82*	−0.99**	−0.89**	−0.76*	−0.92**	−0.90**	−0.99**	−1.29***	−1.35***	−1.30***	−1.23***	−1.26***	−1.23**	−1.25***
	[0.41]	[0.44]	[0.45]	[0.35]	[0.42]	[0.43]	[0.35]	[0.43]	[0.42]	[0.46]	[0.44]	[0.44]	[0.36]	[0.54]	[0.33]
(log) Lightning	−0.16**				−0.093	−0.064	0.024	0.066	0.029	0.15					
	[0.076]				[0.10]	[0.092]	[0.057]	[0.081]	[0.086]	[0.15]					
Computer at home, 2003		0.028**			0.017			0.0063	0.021	0.051	0.029				
		[0.012]			[0.016]			[0.036]	[0.037]	[0.039]	[0.036]				
Access to Internet at home, 2003			0.033***			0.026*		0.0064	0.0019	−0.0095	0.0051				
			[0.011]			[0.014]		[0.036]	[0.036]	[0.038]	[0.037]				
Manufacturing firms' IT investments, 2007				0.16***			0.17***	0.17***	0.15***	0.15***	0.13***	0.13***	0.14***	0.13**	0.15**
				[0.025]			[0.027]	[0.029]	[0.034]	[0.038]	[0.034]	[0.033]	[0.031]	[0.064]	[0.062]
Observations	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
R^2	0.15	0.15	0.19	0.57	0.17	0.20	0.57	0.58	0.62	0.71	0.70	0.67	0.60	.	.
Instrumented variable	.	.	.	.	.	.	.	.	.	.	.	.	.	Manufacturing Firms' IT Investments, 2007	
Instrument	.	.	.	.	.	.	.	.	.	.	.	.	.	(log) Lightning	
1st-stage F-statistic (Kleibergen-Paap Wald F-statistic)	.	.	.	.	.	.	.	.	.	.	.	.	.	6.96	14.38
Weak-instrument robust inference: Stock-Wright LM S statistic (p-value)	.	.	.	.	.	.	.	.	.	.	.	.	.	0.061	0.067
Human capital controls (enrollment, high school or higher, B.A.)	No	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Regional fixed effects (8 BEA economic regions)	No	No	No	No	No	No	No	No	No	Yes	Yes	Yes	No	Yes	No
H_0: Regional FEs = 0 (p-value)	.	.	.	.	.	.	.	.	.	0.24	0.24	0.32	.	0.12	.

OLS and IV estimates. The dependent variable in all regressions is the average annual growth rate in GSP per worker over the period 1991–2007. Columns 14 and 15 report 2SLS regressions, where manufacturing firms' IT investments are instrumented by (log) lightning density. Access to a computer and Internet at home are measured as the percentage of households by state. IT investments at manufacturing firms are measured as the percentage of capital expenditures on computers and data processing equipment, relative to all nonconstruction capital expenditures for all firms in the manufacturing sector. Lightning is the average number of flashes per year per square kilometer, measured by flash detectors. All regressions include a constant. Robust standard errors in brackets. Significant at the ***1%, **5%, and *10% levels.

FIGURE 10.—EXOGENOUS COMPONENT OF MANUFACTURING FIRMS' ICT CAPITAL EXPENDITURE TO TOTAL CAPITAL EXPENDITURE AND ECONOMIC GROWTH, 1991–2007



Estimated by 2SLS.

growing influence of digital technologies on economic growth.

IV. Conclusion

In theory, lightning should have an impact on IT diffusion. Higher lightning intensity leads to more frequent power disruptions, which in turn reduces the longevity of IT equipment. As a result, by inducing higher IT user cost, a higher lightning frequency should hamper IT investments. By implication, high-tech societies may actually be quite vulnerable to climate shocks. Consistent with the temperate drift hypothesis, technological change may therefore render societies more sensitive to climate phenomena that previously were of only second-order importance.

Empirically we document that lightning activity is negatively correlated with measures of IT diffusion: computers and Internet hookups per household and IT investment rates by manufacturing firms. Conditional on standard controls, states with less lightning have adopted IT more rapidly than states where lightning activity is more intensive.

Consistent with a detrimental impact on IT diffusion, we find that states with more lightning have grown more slowly about 1990. This pattern cannot be accounted for by other climate phenomena or explained by a time-varying influence from deep historical determinants of productivity.

REFERENCES

Acemoglu, Daron, Simon Johnson, and James Robinson, "The Colonial Origins of Comparative Development: An Empirical Investigation," *American Economic Review* 91 (2001), 1369–1401.

——— "Reversal of Fortune: Geography and Institutions in the Making of the Modern World Income Distribution," *Quarterly Journal of Economics* 117 (2002), 1231–1294.

——— "The Rise of Europe: Atlantic Trade, Institutional Change, and Economic Growth," *American Economic Review* 95 (2005), 546–579.

Angrist, Joshua, and Jörn-Steffen Pischke, *Mostly Harmless Econometrics* (Princeton, NJ: Princeton University Press 2009).

Ashraf Quamrul, and Oded Galor, "Dynamics and Stagnation in the Malthusian Epoch: Theory and Evidence," Brown University working paper (2008).

Barro Robert J., and Xavier Sala-i-Martin, "Convergence," *Journal of Political Economy* 100 (1992), 223–251.

——— *Economic Growth* (New York: McGraw, Hill, 1995).

Beaudry, Paul, Mark Doms, and Ethan Lewis, "Endogenous Skill Bias in Technology Adoption: City-Level Evidence from the IT Revolution," Federal Reserve Bank of San Francisco working paper no. 2006-24 (2006).

Brynjolfsson, Erik, and Lorin M. Hitt, "Computing Productivity: Firm Level Evidence," this REVIEW 85 (2003), 793–808.

Bundesamt für Sicherheit in der Informationstechnik, *IT-Grundschutz Manual*. (2004). http://www.bsi.de/english/gshb/index.htm.

Cameron, A. Colin, and Pravin K. Trivedi, *Microeconometrics* (Cambridge: Cambridge, University Press, 2005).

Caselli, Francesco, and Wilbur J. Coleman II, "Cross-Country Technology Diffusion: The Case of Computers," *American Economic Review* 91 (2001), 328–335.

Chinn, Menzie D., and Robert W. Fairlie, "The Determinants of the Global Digital Divide: A Cross-Country Analysis of Computer and Internet Penetration," *Oxford Economic Papers* 59 (2007), 16–44.

Chisholm, William, "Lightning Protection," L. Grigsby (Ed.), in *The Electrical Power Engineering Handbook* (Piscataway, NJ: IEEE Press, 2000).

Chisholm, William, and Kenneth Cummins, "On the Use of LIS/OTD Flash Density in Electric Utility Reliability Analysis," in *Proceedings of the LIS International Workshop, MSFC, Huntsville, AL* (September 2006).

Diamond, Jared, *Guns, Germs and Steel: The Fates of Human Societies* (New York: Norton, 1997).

Dell, Melissa, Benjamin Jones, and Benjamin Olken, "Climate Change and Economic Growth: Evidence from the Last Half Century," NBER working paper no. 14132 (2008).

——— "Temperature and Income: Reconciling New Cross-Sectional and Panel Estimates," *American Economic Review Papers and Proceedings* 99 (2009), 198–204.

Emanuel, A. E., and J. A. McNeill, "Electric Power Quality," *Annual Review of Energy and the Environment* 22 (1997), 263–303.

Engerman, Stanley L., and Kenneth L. Sokoloff, "Factor Endowment, Inequality, and Paths of Development among New World Economies," NBER working paper no. 9259 (2002).

Galor, Oded, Omar Moav, and Dietz Vollrath, "Inequality in Land Ownership, the Emergence of Human Capital Promoting Institutions, and the Great Divergence," *Review of Economic Studies* 76 (2009), 143–179.

Hall, Robert E., and Dale W. Jorgenson, "Tax Policy and Investment Behavior," *American Economic Review* 57 (1967), 391–414.

Jorgenson, Dale W., "Information Technology and the US Economy," *American Economic Review* 91 (2001), 1–32.

Kressel, Henry, *Competing for the Future: How Digital Innovations Are Changing the World* (Cambridge: Cambridge University Press, 2007).

Kunkel, Kenneth E., Roger A. Pielke Jr., and Stanley A. Changnon, "Temporal Fluctuations in Weather and Climate Extremes That Cause Economic and Human Health Impacts: A Review," *Bulletin of the American Meteorological Society* 80 (1999), 1077–1098.

Mitchener, Kris James, and Ian W. McLean, "The Productivity of US States since 1880," *Journal of Economic Growth* 8 (2003), 73–114.

National Energy Technology Laboratory, *The Value of Electricity When It's Not Available* (2003). http://www.netl.doe.gov/moderngrid/docs/The_Value_of_Electricity_When_It's_Not_Available.pdf.

Nelson, Richard R., and Edmund S. Phelps, "Investment in Humans, Technological Diffusion, and Economic Growth," *American Economic Review* 56 (1966), 69–75.

Nordhaus, William D., "Geography and Macroeconomics," *Proceedings of the National Academy of Sciences (US)* 103 (2006), 3510–3517.

Olsson, Ola, and Douglas Hibbs Jr., "Biogeography and Iong-run Economic Development," *European Economic Review* 49 (2005), 909–938.

Phelps, Edmund S., "The New View of Investment: A Neoclassical Analysis," *Quarterly Journal of Economics* 76 (1962), 548–567.

Putterman, Louis, "Agriculture, Diffusion, and Development: Ripple Effects of the Neolithic Revolution," *Economica* 75 (2008), 729–748.

Rappaport, Jordan, and Jeffrey D. Sachs, "The US as a Coastal Nation," *Journal of Economic Growth* 8 (2003), 5–46.

Rodrik, Dani, Arvind Subramanian, and Francesco Trebbi, "Institutions Rule: The Primacy of Institutions over Geography and Integration in Economic Development," *Journal of Economic Growth* 9 (2004), 131–165.

Shim, Jae K., Anique Qureshi, and Joel G. Siegel, *The International Handbook of Computer Security* (Chicago: Glenlake Publishing Company, 2000).

Yeager, Kurt, and Karl Stahlkopf, "Power for a Digital Society," Department of Energy CF-170/1–1-DOE. (2000). http://www.rand.org/scitech/stpi/Evision/Supplement/yeager.pdf.