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CLIMATE, ECOSYSTEM RESILIENCE AND THE SLAVE TRADE

JAMES FENSKE[†] AND NAMRATA KALA[*]

ABSTRACT. African societies exported more slaves in colder years. Lower temperatures reduced mortality and raised agricultural yields, lowering slave supply costs. Our results help explain African participation in the slave trade, which predicts adverse outcomes today. We use an annual panel of African temperatures and port-level slave exports to show that exports declined when local temperatures were warmer than normal. This result is strongest where African ecosystems are least resilient to climate change. Cold weather shocks at the peak of the slave trade predict lower economic activity today. We support our interpretation using the histories of Whydah, Benguela, and Mozambique.

1. INTRODUCTION

The slave trade is critical to understanding African poverty. Regions of Africa that exported a higher number of slaves suffered selective depopulation (Manning, 1990) and diverted efforts from productive activities towards the harvesting of slaves (Whatley and Gillezeau, 2011a). Today, these regions have lower incomes (Nunn, 2008), are less trusting (Nunn and Wantchekon, 2011), have more polygamy (Dalton and Leung, 2011), and are more ethnically divided (Whatley and Gillezeau, 2011b). Despite the importance of the slave trade, little is known about the influence of African factors on the supply of slaves. Whatley's (2008) estimates of the guns-for-slaves cycle is the only empirical study of African supply dynamics of which we are aware. Our focus is on supply-side environmental shocks.

Our approach is to use reconstructed annual data on African temperatures to measure the year-to-year variation in weather conditions over space during the time of the transatlantic slave trade. We use this data to construct port-specific annual temperature shocks, and combine these with port-level annual slave exports. The panel nature of this data allows us to control both for port-level heterogeneity and for the flexible evolution of the slave trade as a whole over time. We find a considerable decrease in the number

[†]UNIVERSITY OF OXFORD
[*]YALE UNIVERSITY
E-mail addresses: `james.fenske@economics.ox.ac.uk`, `namrata.kala@yale.edu`.
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of slaves shipped from ports in warmer years. This result is robust to several alternative specifications, including aggregated units of observation, addition of port-specific time trends, and estimation on sub-samples partitioned over time and space. In addition to studying annual temperatures, we also examine the role of longer-term environmental factors by looking at the effect of climate (that is, long-run trends in temperature) on slave exports, and find effects that are the same in sign and much larger in magnitude.[1]

Our interpretation is that warmer temperatures led to increased costs of raiding for slaves. These are years of lower productivity for agriculture (Kurukulasuriya and Mendelsohn, 2006; Lobell and Field, 2007; Tan and Shibasaki, 2003) and of greater mortality (Burgess et al., 2009). In our baseline specification, the magnitude of the impact of a 1°C temperature shock is roughly equal to the mean slave exports from an active port. We argue that this effect worked through higher costs of collecting taxes and tribute for local states, lower productivity in supporting sectors of the economy, greater disorder in the regions where slaves were usually captured, and higher slave mortality. We validate our interpretation using case studies of three ports that are influential in our results: Benguela, Whydah, and Mozambique. Our results confirm the importance of supply-side environmental factors in accounting for the transatlantic slave trade.

We show that the effect we find is stronger in Africa's sub-humid and dry savannah regions than it is in areas of moist savannah and humid forest. That is, the regions of Africa in which agricultural productivity is most sensitive to fluctuations in temperature (Seo et al., 2009) were those that responded most in terms of slave exports. Further, we find that both long-run trends in climate and short-run shocks around these trends have power to explain variation in slave exports. Using modern-day light density at night to proxy for economic activity, we find that the regions around ports that received cold temperature shocks at the peak of the trans-Atlantic slave trade are poorer today.

Our results help explain the relationship between the environment and development. A large literature has emphasized the role of geography in shaping economic outcomes in the present (Gallup et al., 1999), through its impact on historical processes (Bleakley and Lin, 2012; Easterly and Levine, 2003), and over the very long run (Ashraf and Galor, 2011; Ashraf and Michalopoulos, 2011). The unchanging nature of geographic endowments makes it difficult to separate their direct effects from their indirect impacts through institutions such as property rights and states (Acemoglu et al., 2001; Fenske, 2012). It is also challenging to separate these from the impacts of local unobservable variables that are correlated with geography. Recent work, then, has used natural experiments such as the eradication of endemic diseases (Bleakley, 2007; Cutler et al., 2010) or variation over time in temperature and rainfall (Brückner and Ciccone, 2011; Dell et al., 2012; Jia, 2011). Abrupt and persistent changes in climate have precipitated the collapse of civilizations through lowered agricultural productivity, depopulation, the decline of

[1]Climate science usually distinguishes between short-run "weather" and long-run "climate." Climate is a statistical description, usually the mean and variability, of relevant quantities over a period of time. As defined by the World Meteorological Organization, this time period is 30 years (IPCC, 2007).

cities and the weakening of states (Barrios et al., 2010; DeMenocal et al., 2001; Haug et al., 2003; Hornbeck, 2012; Weiss and Bradley, 2001). The mechanisms for these effects are not yet fully understood. We give evidence that the impact of temperature shocks on sectors outside of agriculture has not been confined to the industrial era, and provide one possible mechanism by which temperature shocks affect modern incomes. We show that even small, short-run changes had large impacts on the productive sectors and coping mechanisms of African societies. The slave trade's effects on modern-day institutions, mistrust and poverty in Africa are, then, partly reflections of the continent's environmental history.

We also add to existing knowledge of the economics of conflict. Strong correlations between economic shocks, economic grievances, and the onset of conflict have been asserted in the literature (Brückner and Ciccone, 2010; Brückner et al., 2012; Miguel et al., 2004), albeit not without controversy (Ciccone, 2011; Miguel and Satyanath, 2011). The proposed mechanisms for this link focus on the greater relative returns to insurrection over other activities and the diminished strength of national militaries during periods of reduced income (Blattman and Miguel, 2010; Fearon and Laitin, 2003). It is not established that the same relationships have held in the past, nor has it been shown whether endemic, parasitic violence will respond in the same way to economic shocks. Violence in Colombia intensifies when coca or oil prices rise (Angrist and Kugler, 2008; Dube and Vargas, 2012), while Japan's long recession has cut into the *yakuza's* profits from racketeering (Hill, 2006, p. 247). The dynamics of the slave trade, then, followed a logic similar to the model of Besley and Persson (2011); greater state revenues encouraged repression (slave raiding) under non-cohesive political institutions. We argue that the returns to the violent harvesting of slaves fell during depressed periods. To the extent that current economic growth attenuates the rise of conflict (Collier and Hoeffler, 2004), we contribute to the literature that explains how history matters for modern conflict.

We also contribute to a more narrow literature in African history. Historians such as Hartwig (1979), Miller (1982), and Searing (1993) have suggested that droughts and famines may have either increased or decreased the supply of slaves. Crises pushed people to sell themselves or their dependants into slavery, but also led to death and dispersion that reduced the availability of slaves for export and the provisions needed to feed them. Lacking consistent data over time and space, these local qualitative studies have been unable to find the net effect of environmental stress on slave supply. We provide the first such estimates.

We proceed as follows. In section 2, we outline our empirical approach and describe our sources of data on temperature shocks and slave exports. In section 3, we provide our baseline results and demonstrate their statistical robustness. We show that that the effect of temperature differs by agro-ecological zone. We decompose the effect of temperature into long-run trends and fluctuations around it. We show the impact of past temperature shocks on modern light density. In section 4, we explain the results. We provide a simple model and argument to account for greater slave exports during years of better agricultural productivity and lower mortality. We discuss evidence from the secondary literature that connects warmer temperatures to increased mortality and reduced agricultural productivity. We support our interpretation by examining case studies of three important slave ports – Whydah, Benguela, and Mozambique. Section 5 concludes.

2. Empirical strategy and data

2.1. **Empirical strategy.** Our data will consist of a panel of annual slave exports and temperatures for 134 ports that were engaged in the transatlantic slave trade. The dependent variable of interest, the number of slaves exported from port i in year t, is bounded below by 0. Thus, our main specification is the following:

$$slaves_{i,t} = max(0, \alpha + \beta\, temperature_{i,t} + \delta_i + \eta_t + \epsilon_{i,t}) \tag{1}$$

Here, $slaves_{i,t}$ is number of slaves exported from port i in year t. $temperature_{i,t}$ is the temperature at port i in year t, δ_i is a port-level fixed effect, η_t is a year fixed effect and ϵ_{it} is the error term. We estimate (1) using a tobit estimator. We use ports as the unit of observation because this is the level at which the data on slave exports are available; we show in section 3.3 that we can find similar results using alternative units of observation.

Standard errors are clustered by the nearest grid point in our temperature data, intersected with year, since there are fewer grid points than there are ports.[2] In addition to using temperature as the key explanatory variable of interest, we also estimate the impacts of the long-run moving average (climate) and variation of temperature around this average (climate shocks) on the supply of slaves.

2.2. **Data.**

2.2.1. *Temperature.* In order to estimate (1), we use three principal sources of data. The first covers temperature. The historical data are reported as temperature "anomalies," and are taken from Mann et al. (1998a,b). They reconstruct annual temperature anomalies using multivariate calibration on a 5° by 5° grid. They use a variety of proxy climate indicators, combining data from several previous paleoclimatic studies that calculated historical temperatures using data from different proxy indicators. These include coral, ice cores, tree rings, and other long instrumental records. The availability of multiple indicators increases the robustness of the estimates, and their calculations account for the appropriate potential limitations of each proxy indicator. They calibrate the proxy dataset using monthly instrumental data from 1920-1995, and compute annual temperature anomalies for each year from 1730 to 1900 relative to the baseline average temperature during the period 1902 to 1980. Additional details of their methodology

[2]We also report standard errors clustered by 1° squares (which is more conservative than clustering by port) and by year.

are available in Mann et al. (1998a,b), and the dataset has been used by numerous climate scientists to study long-term climate warming trends (Covey et al., 2003; Crowley, 2000; Huang et al., 2000). A temperature anomaly of $1°C$ at port i in year t means that the temperature at i was $1°C$ higher during t than the mean temperature at i over the period 1902-1980. We reconstruct the baseline temperatures for each port using a separate temperature series from the University of Delaware, which covers the 1902-1980 period. This permits us to convert the anomalies into an annual temperature series for each port.[3]

In addition to using these temperatures directly, we convert them into fluctuations around longer-run climate trends by removing the 30-year running mean from each port. These are then treated as shocks over and above the long-term trend in climate. In our analysis, we also use this running mean of climate as a regressor to estimate the impact of changes in longer-run climate on the dynamics of the slave trade. Where data are missing on the 5° by 5° grid, we impute anomalies separately for each year using a cubic polynomial in latitude and longitude, with full interactions. Because our data are annual, we are unable to isolate temperature shocks during critical months in the agricultural calendar. This attenuation bias will push our results towards zero.

2.2.2. *Slave exports.* The second source of data that we use is the Trans-Atlantic Slave Trade Database of Eltis et al. (1999).[4] The trans-Atlantic slave trade, which is the focus of this study, comprised roughly two thirds of the volume of slaves transported from Africa between 1400 and 1900 (Nunn, 2008). Because the temperature data are only available after 1730, we are confined to analyzing the the impact on the slave trade during this period. Since the overwhelming bulk of slaves were shipped across the Atlantic in this period, we are able to study the slave trade when it was at its most active. The database provides voyage-level data on more than 34,000 voyages, including information on the number of slaves carried, the year the ship departed Africa, and the principal port of slave purchase.

We convert these raw data into an annual port-level panel. Since not all ships embarked from known ports or, in some cases, known regions, this requires assigning several of the slaves to ports. 60% of slaves come from ports with known latitude-longitude coordinates. 20% come from a known region (such as the Bight of Benin) but with no port given in the raw data. 20% come from voyages in which only the year is known.[5] We assign slaves from ships from known regions and unknown ports in proportion to

[3]Baseline temperatures can be downloaded from `http://climate.geog.udel.edu/~climate/html_pages/download.html#P2009`. We originally downloaded the historical anomalies from `http://picasso.ngdc.noaa.gov/paleo/data/mann/`. These have since been moved to `http://www.ncdc.noaa.gov/paleo/pubs/mann1998/frames.htm`, and we are willing to provide the data on request. Vlassopoulos et al. (2009) have used these data previously.

[4]The database is online, at `http://www.slavevoyages.org`.

[5]Fewer than 1% of slaves in the data come from ports to which we have been unable to assign geographic coordinates. We treat these ports as observations with a known region, but no known port.

the number of slaves that are exported from the known ports within that region in a given year. Analogously, we assign slaves from ships from unknown regions and unknown ports in proportion to the number of slaves that are exported from all known ports within a given year. We obtain a panel of 134 ports spanning 137 years, from 1730 to 1866.

Temperature shocks for each port are computed by taking the four nearest points in the temperature data and interpolating bilinearly. We treat these as proxies for conditions within the catchment zone of each port, since the vast majority of slaves came from areas within 100 miles of the coast (Evans and Richardson, 1995, p. 675). We map both the temperature points for which Mann et al. (1998a) report their data and the ports reported in the Trans-Atlantic Slave Trade Database in Figure 1. Summary statistics for our sample are given in Table 1. A kernel density plot of slave exports is included in Appendix A. The mean number of slaves exported annually per port is close to 450, and increases to roughly 2,500 when we only consider ports that exported a non-zero number of slaves in a given year. The standard deviation reported in the table conflates differences in temperatures across ports with within-port variation. The standard deviation of temperature with port means removed is roughly 0.16 $1^{\circ}\mathrm{C}$.

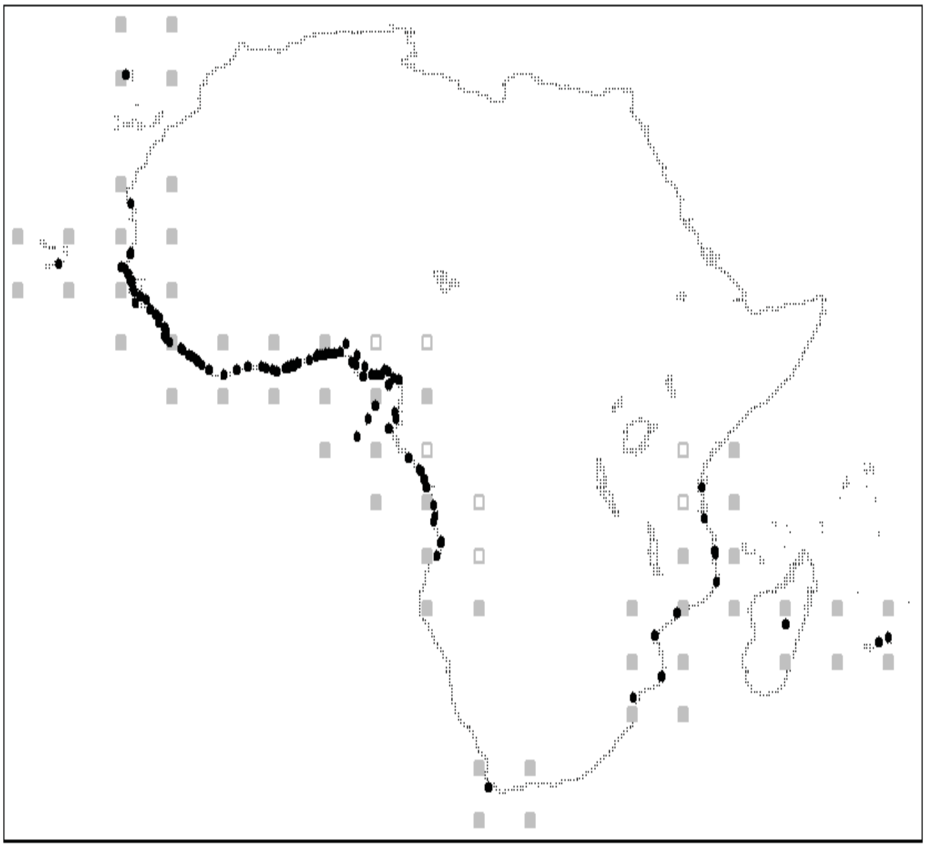
2.2.3. *Agro-ecological zones.* The third source of data is on agro-ecological zones (AEZs). These data classify land into zones based on climate, elevation, soils and latitude, and are compiled by the Food and Agriculture Organization (FAO). The original AEZ classification classifies land in Africa into 16 zones, which includes five climatic zones each at three levels of elevation (high, medium and low), and the desert. These AEZs are stable across time, since they are classified using factors such as long-term climate, soil, elevation and latitude. To estimate the effects of temperature separately by AEZ, we collapse the same ecological zone at each elevation into a single classification. For instance, we classify high-elevation dry savannah, mid-elevation dry savannah and low-elevation dry savannah all as “dry savannah”. Ports are assigned the AEZ of the nearest African administrative unit in the data used by Kala et al. (2011). The 134 ports in our data comprise desert, dry savannah, moist savannah, sub-humid, and humid forest zones.

3. Results

3.1. **Main results.** We present our main results in Table 2. We find that a one degree increase in temperature leads to a one-year drop of roughly 3,000 slaves from the treated port. This is a sizeable effect, roughly equal to the mean for a port whose exports are nonzero in a given year. For a one standard deviation increase in de-meaned temperature (roughly $0.16^{\circ}\mathrm{C}$), the effect would be about 480 slaves.[6] This is roughly a one quarter of a standard deviation movement in slave exports.

[6]This is smaller than the standard deviation reported in Table 1, since that figure reflects variations in temperature across ports, rather than fluctuations experienced by individual ports over time.

FIGURE 1. Map of ports and temperature points



The solid black circles are the ports that appear in the Trans-Atlantic Slave Trade Database. The grey squares are the points of the 5° by 5° grid on which Mann et al. (1998a) record temperature anomalies. Hollow squares are points that were missing in Mann et al. (1998a), and that we imputed using a polynomial in latitude and longitude.

Scientific evidence indicates that the process of multi-proxy historical temperature reconstruction may create a temperature series with dampened variability (Christiansen and Ljungqvist, 2011; Riedwyl et al., 2009; von Storch et al., 2004). This dampening would scale up our estimated coefficient. In the baseline period 1902-80, the port-specific temperature anomalies have a standard deviation of $0.42°\text{C}$. If our historical temperature data have been dampened by the ratio $0.16/0.42$, then our coefficient estimates should be re-scaled by this same ratio. This gives a slave supply response to a $1°\text{C}$ temperature shock of roughly 1200 fewer slaves. This is approximately a two thirds of a standard deviation reduction in slave exports.

While it is possible that temperature has non-linear impacts on slave exports, the linear relationship is a good approximation of this effect. One of our primary proposed mechanisms is the link between temperature and agricultural productivity, discussed in section 3.2. Studies of this relationship in Africa find small and often insignificant effects of higher-order polynomial terms in temperature (Kurukulasuriya et al., 2011; Kurukulasuriya and Mendelsohn, 2006). Further, studies linking temperature to economic outcomes generally rely on linear specifications (Burgess et al., 2009; Dell et al., 2012). If we include a quadratic term for temperature, we find that the marginal effect is smaller at greater temperatures, diminishing from roughly -5000 at $20°\mathrm{C}$ to roughly -2600 at $25°\mathrm{C}$ (not reported).

Though this magnitude may appear large, a one-degree higher temperature over an entire year is a significant shock. Dell et al. (2012) show that a one degree temperature increase is associated with lower economic growth by about 1.3 percentage points in poorer countries, and impacts both the agricultural and industrial sectors.

3.2. **Mechanisms.**

3.2.1. *Results by ecological zone.* In Table 3, we show the results differ across African agro-ecological zones (AEZs). The general pattern that emerges is that the elasticity of slave exports with respect to temperature is greater in drier environments. Although greater slave mortality may partially explain smaller exports in warmer years, these results suggest that agricultural productivity was an important channel. These are the regions in which agriculture would be most sensitive to fluctuations in weather (Seo et al., 2009). The largest impact is on dry savannah and deserts followed by sub-humid zones, and the lowest impacts are on moist savannah and humid forest. There are only four ports classified as desert, and so we focus our attention on the impacts of temperature on the other zones.

Kala et al. (2011) analyze current agricultural productivity by AEZ, and find that moist savannah and sub-humid zones, where the impacts of temperature on slave exports are relatively minor, are more productive in general than dry savannah zones. At high and mid-elevations, sub-humid zones can have productivity similar to (or even greater than) that of moist savannahs. This helps explain why both have intermediate coefficients between the large impact on dry savannah and the negligible impact on humid forest. Other analyses of ecological zones in Africa find that the growing season is longer in sub-humid and humid zones than in semi-arid and arid zones (Bationo et al., 1998). Plant growth potential is is also higher in sub-humid and humid areas (Ojwang et al., 2010). Both tendencies make these areas less vulnerable to shocks.

While mortality was likely a mechanism driving the impact of higher temperatures, the differential relationship between temperature and disease by humidity provides further support for an agricultural productivity interpretation. Higher temperatures are more likely to exacerbate the disease burdens of malaria and trypanosomiasis in humid regions (Munang'andu et al., 2012; Yé et al., 2007), and we see larger impacts of higher temperatures in dry ecological zones. Together, these results suggest that the effects of temperature shocks on the slave trade operated through agricultural productivity, and were most deeply felt in the parts of Africa with the least resilient ecosystems.

3.2.2. *Climate.* In Table 4, we show that both the thirty-year moving average of temperature and fluctuations around it can explain slave exports. Both coefficients have negative signs. Warmer trends and unusually warm years reduce slave exports. A one degree anomaly over the 30-year climate mean has an average impact of nearly 1,300 fewer slave exports per port per year, similar to our main temperature measure, whereas a one degree increase in the 30-year climate mean has an average impact of nearly 18,000 fewer slave exports per port per year. The impact of a warm trend is much larger than an unusually warm single year. A one standard deviation change in within-port climate causes about 1,800 fewer slaves to be exported per port per year on average.

Part of this difference may be purely mechanical. The within-port variance of the temperature anomalies is greater than that of the climate anomalies, and the trend for climate will smooth over year-to-year measurement error in temperature. However, the greater impact of a warming trend is also consistent with the mechanisms through which we argue that environmental factors affected the slave trade. The cumulative impact of a warming trend on agricultural productivity and mortality are greater than for a single warm year. Over time, these will lead to depopulation and out-migration, making slave exports increasingly unviable. Though societies may adapt to sustained climate change, a prolonged period of worsening climate can lead to social collapse (DeMenocal et al., 2001; Haug et al., 2003).

3.2.3. *Modern impact.* While colder years improved agricultural productivity, they also increased slave exports. The density of modern night-time lights – a proxy for economic activity – can be used to identify which effect dominated over the long run.[7] Michalopoulos and Papaioannou (2012) provide documentation for these data, and show that pre-colonial institutions in Africa predict contemporary economic activity captured by light density. For each of our 134 ports, we calculate the average light density in 2009 within 500 km. We then use OLS to estimate:

$$\ln(lightdensity_i) = \beta anomaly_i + x_i'\gamma + \epsilon_i. \tag{2}$$

Here, $anomaly_i$ is the accumulation of temperature anomalies over the slave trade as a whole, or over selected periods. x_i is a vector of controls that includes a constant, absolute latitude, longitude, the number of raster light density points within 500km of the port, dummies for AEZs, distance from the nearest Atlantic or Indian Ocean port of slave demand, and average temperature over the period 1902-1980. Robust standard errors are used for this cross-sectional regression. Our results are still significant at the 10% level when Conley (1999) standard errors are adjusted for spacial dependence over distances of ten decimal degrees. We report results in Table 5. Past temperature shocks predict higher incomes in the present, suggesting that the long-run reduction in slave exports out-weigh the transient losses to agriculture. In particular, it is temperature

[7]These are downloaded from `http://www.ngdc.noaa.gov/dmsp/global_composites_v2.html`.

shocks during the late eighteenth century peak of the slave trade that best predict luminosity in the present.

3.2.4. *Other possible mechanisms.* Higher temperatures directly reduce agricultural productivity in Africa. In addition, they predict lower rainfall, which we are unable to observe during the time period covered by our data. Our result, then, mixes the direct impact of temperature with indirect effects that operate through rainfall. To establish the size of the correlation between temperature and rainfall, we use data on temperature and precipitation from the University of Delaware.[8] These report annual temperature and precipitation figures for points spaced every 0.5° by 0.5° from 1900 to the present. We confine our analysis to points in Africa during the years 1900-2000. We regress the log of annual rainfall on the log of annual temperature, point fixed effects and year fixed effects. We find that a one percent temperature increase is associated with lower rainfall of 1.26 percent, with a standard error of 0.028. Though this is a large elasticity, temperature shocks explain less than 1% of the variance in rainfall fluctuations.[9] While our main result captures the combination of higher temperatures and lower rainfall on the supply of slaves, this suggests that the direct effect of temperature on agriculture and mortality is what drives our results.[10]

An alternative reading of our results would infer that higher temperatures were associated with greater natural hazards for transatlantic shippers, and that our results do not reflect "supply side" shocks within Africa. As evidence against this interpretation, we make use of additional data from the Trans-Atlantic Slave Trade Database. For 18,942 voyages that have a known year of travel and a known region or port of slave purchase, the data also record whether the journey was completed successfully, failed due to a human hazard, or failed due to a natural hazard. In this sample, we regress the occurrence of a natural hazard on temperature, port fixed effects, and year fixed effects. To compute a temperature for ships without known ports, we assign ships to the modal port in the region of slave purchase. We find that a $1°C$ temperature increase reduces the probability of a natural hazard by 10.4 percentage points, with a standard error of 3.5 percentage points. Warmer years were associated with fewer natural hazards for those who shipped slaves across the Atlantic. Our main result works in the opposite direction, and overcomes this effect.

A third possible explanation for our results is that wind speeds were higher in colder years, which enabled ships to make a greater number of voyages than in warmer years. There are several reasons why this is not a main driver of our results. First, as discussed

[8]These are available at `http://climate.geog.udel.edu/~climate/`.

[9]That is, regressing the partial residuals from a regression of log rainfall on the point and year fixed effects on the partial residuals from a regression of log temperature on these same fixed effects gives an R-squared of less than 0.01.

[10]We have also performed this same regression using levels, rather than logs, and using binary indicators for whether rainfall or temperature are above their historical means. Both of these give results consistent with the log specification.

in section 3.2.1, the impacts of temperature are heterogenous by agro-ecological zone, which would not be the case if the results were driven by lower temperatures enabling the ships to complete more voyages due to increased ship speeds.

Second, we use modern data on temperature and wind speed to show that higher temperatures only lead to small declines in wind speeds in the present. We use modern day (1950-2000) temperature and wind speed data from the Laboratoire de Météorologie Dynamique.[11] We regress annual wind speed on annual temperature, controlling for year and point fixed effects. A one degree Celsius increase in temperature leads to a 0.01 meters/second (m/s) increase in wind speed globally, and a -0.02 m/s decrease in wind speed in the geographic region in Africa. These effects are quite small relative to the mean wind speed, which is 3.2 m/s at the global level and 2.99 m/s around the region near Africa. Even though there is a negative association between temperature and wind speed in and around Africa, the magnitude is only about 1% of the mean, and it explains very little of the variation in wind speeds.[12]

It is also unlikely that voyage lengths are driving our result. Shippers had limited scope to lengthen their buying periods in response to diminished African supply. Because labor and borrowing costs increased with the length of a voyage, European traders were keen to minimize their time on the African coast (Miller, 1996, p. 327). Miller (1981, p. 414) estimates that slaves in eighteenth-century Angola typically waited one month in barracoons at the coast before being loaded onto a slave ship. Of the voyages for which the time between departure from home port and departure from Africa are known, fewer than 10% spent longer than one year in Africa. A kernel density of this distribution is reported in Appendix A.

Another alternate interpretation of our findings would link higher temperatures with greater productivity in cattle-keeping. In humid forest regions, higher temperatures increase the prevalence of tsetse flies, which increases morbidity and mortality of both men and cattle, due to the spread of sleeping sicknesses. In drier zones, however, higher temperatures kill the tsetse, benefitting cattle production (Pollock, 1982). We use three tests to show that this mechanism does not explain our results. First, we use the Murdock (1967) *Ethnographic Atlas* to identify the percentage of societies within 500km of each port who possess bovine animals.[13] Including the interaction between temperature and average bovine presence does not diminish the main effect (see Table A1, in the appendix). The interaction effect is positive (not reported), suggesting that the effect of temperature is in fact *weaker* in areas that keep cattle.

[11]A detailed explanation of the data and the analysis is available in appendix C.

[12]That is, regressing the partial residuals from a regression of wind speed on the point and year fixed effects on the partial residuals from a regression of temperature on these same fixed effects gives an R-squared of 0.003.

[13]We use the latitude-longitude coordinates provided in the *Atlas* to identify the locations of these ethnic groups. The presence of bovine animals is an indicator equal to 1 if variable $V40$ is equal to 7, if $V40$ is non-missing. If there are no societies within 500km, we use the nearest society in the *Atlas*.

Similarly, we use the *Ethnographic Atlas* to calculate the average dependence on animal husbandry for the societies within 500km of each port.[14] Including the interaction between temperature and dependence on husbandry again does not diminish the main effect (Table A1). The interaction is positive, but not significant. Third, we include the interaction between temperature and the suitability of the area within 500km of each port for tsetse.[15] Yet again, this does not diminish the main effect (Table A1). The interaction is positive, but not significant (not reported).

3.3. **Robustness.** We have tested the robustness of our main result to multiple checks for unobserved heterogeneity, measurement of slave exports and temperature shocks, the unit of observation, outliers, the estimation method, and the inclusion of lag slave exports as a control. The results of these tests are presented in the appendix. In some specifications, we were unable to compute clustered standard errors using temperatures, and so anomalies (with nearly identical point estimates) were used in their place. These are indicated in the tables.

3.3.1. *Heterogeneity.* To account for port-specific heterogeneity, we have allowed for port-specific linear trends and region-specific quadratic trends.[16] We also estimate (1) on the sub-samples before and after British abolition of the slave trade in 1807. This shows both that a major break in the demand structure of the slave trade does not affect the supply-side link between temperature and slave exports, and that the results survive despite the relatively poor data available for individual ships after 1807.[17] Estimating the results separately for every 25-year interval in the data, we find a negative coefficient in more than 90% of intervals. It is significant at the 5% level during the intervals centred from 1742-58, 1780-90, and 1827-1845. We find no evidence that the effect of temperature differed during years with El Niño events (not reported).[18]

We cannot estimate the effect of demand shifts in the slave trade as a whole, since these are collinear with the year fixed effects used in our principal specification. We can, however, account for port-specific changes in demand by destination region by including the temperature shock experienced at the nearest new world slave port. These ports are, as in Nunn (2008), Virginia, Havana, Haiti, Kingston, Dominica, Martinique, Guyana, Salvador, and Rio. Similarly, we show that the results are robust to including

[14]Dependence on husbandry is variable $V4$. If there are no societies within 500km, we use the nearest society in the *Atlas*.

[15]Tsetse suitability is raster data downloaded from `http://ergodd.zoo.ox.ac.uk/paatdown/index.htm`. This is only available for mainland Africa, and so these regressions exclude Madagascar and ports more than 500km from the mainland.

[16]Convergence could not be achieved with port-specific quadratic trends using the tobit estimator. If these are included in an OLS estimation, the impact of temperature on slave exports remains negative and significant.

[17]We discuss missing data in greater detail in Appendix B.

[18]We identify El Niño events using the list provided by `https://sites.google.com/site/medievalwarmperiod/Home/historic-el-nino-events`. This list uses Couper-Johnston (2000) as its principal source.

slave prices, both in the embarkation region and in the nearest new world port.[19] Alternatively, we use the disembarkation ports listed in the Trans-Atlantic Slave Trade Database to create a modal destination for each African port. Controlling for the anomaly at these modal destinations also does not change the result. Controlling for the 30-year climate trend at the modal destination causes the coefficient on temperature to fall by roughly 15%, though it remains significant (not reported). The effect becomes larger in magnitude and remains significant if we also control for the temperature shock at each port's nearest neighbor (not reported). Interacting temperature shocks with mean slave exports gives suggestive evidence that the effect is larger for more important ports, but this interaction term is marginally insignificant (not reported). We find no evidence in the cross-section of ports that a greater overall variance of temperature shocks predicts greater average slave exports (not reported).

3.3.2. *Measurement.* We show that the method used to assign slaves to ports is not driving the results. We use only the slaves from known ports to calculate port-by-year exports, and achieve similar results to our baseline approach. The effect is smaller, but in proportion to the smaller standard deviation of the dependent variable. The results also survive when using slaves from known ports or regions only. Results are similar if we use slaves disembarked in the new world, rather than slaves embarked from Africa (not reported). Results remain negative and significant if slave exports are normalized by the population density of the area within 500 km of each port in 1700 (not reported).[20]

Similarly, we show that our results are not an artefact of the bilinear interpolation used to construct port-specific temperatures. We can use the temperature calculated from the closest point in the temperature data and achieve similar results to our baseline. We use the natural log of temperature as an alternative measure of weather shocks, in order to account for possibly multiplicative measurement error. The result is still negative and significant (not reported). It is also negative and significant if the log of (one plus) slave exports is used as the dependent variable (not reported).

Because we do not know the slave catchment areas for each port, we measure temperature shocks at ports rather than in the interior. As an alternative, we compute temperature shocks experienced by the ethnic groups surrounding each port. For each port, we identify the ethnic groups mapped by Murdock (1959) that have centroids within 500 km of of the port. For each of these groups, we use the temperature point closest to the group's centroid to compute annual temperatures. For these same groups, Nunn and

[19]Prices in Africa and the new world are taken from Eltis and Richardson (2004) and cover the years 1671-1810. There are many gaps in these series, especially for the New World ports. These are interpolated linearly using the values of the non-missing prices. For example, gaps in the prices of Senegambian slaves are imputed from the prices in the other African regions. The prices in Eltis and Richardson (2004) are reported for five year intervals. We treat prices as constant within these intervals.

[20]Historical population density is taken from the History Database of the Global Environment (HYDE) version 3.1. This raster data on historical population can be downloaded from `ftp://ftp.mnp.nl/hyde/hyde31_final`. Documentation of the data is provided elsewhere (Bouwman et al., 2006; Klein Goldewijk, 2005; Klein Goldewijk et al., 2010).

Wantchekon (2011) report the number of slaves exported across the Atlantic over the course of the entire slave trade. We use these sums to weight the temperature shocks for the ethnic groups surrounding each port, thus constructing an "interior ethnic groups" shock for each port. As reported in the appendix, these interior shocks have an effect with a magnitude close to our baseline. Results are similar if cutoffs of 250km or 1000km are used for assigning ethnic groups to ports (not reported).

We also validate the use of temperatures at coastal ports as a proxy for conditions in the interior by showing that temperature shocks in modern data are strongly correlated over space. We collect data on annual African temperatures from 1980-2000, reported on a $0.5°$ by $0.5°$ grid by the University of Delaware.[21] To make the estimation computationally feasible, we reduce the resolution of this data to a $3°$ by $3°$ grid. Creating every pairwise merge between ports in the data, we test whether temperatures at point j affect temperatures at point i by estimating:

$$temperature_{it} = \sum_{k=1}^{K} \beta_k D_{ij,k} \times temperature_{jt} + \delta_{ij} + \eta_t + \epsilon_{ijt} \tag{3}$$

Here $D_{ij,k}$ is a dummy variable for whether point i and j are within distance band k. We use 100 kilometer distance bands (200-300 km, 300-400 km, and so on). δ_{ij} is a fixed effect for each pair i, j. η_t is a year fixed effect, and ϵ_{ijt} is error. We show in the appendix that shocks are remarkably persistent across space. For example, the β_k corresponding to a distance band of 500 km to 600 km suggests that a $1°C$ shock between 500 and 600 km away raises local temperature by slightly more than $0.5°C$. Temperatures measured at ports, then, are valid proxies for conditions in the interior.

3.3.3. *Level of observation.* Our results are not sensitive to the use of ports as the unit of observation. We collapse the African coastline into grid squares one degree in longitude by one degree in latitude. We take the sum of all slaves exported from within that grid square as slave exports, and the average temperature for ports within that square as the temperature for that square. The results are very similar to our baseline specification. Results are similar if they are collapsed into squares five degrees by five degrees. This is equivalent to collapsing to the nearest point in the climate data. Similarly, if we collapse slave exports into the major regions of the slave trade (Senegambia, Sierra Leone, the Windward Coast, the Gold Coast, the Bight of Benin, the Bight of Biafra, West-Central Africa, and Southeastern Africa), again using the average temperature across ports within a region to measure the aggregated temperature, we find a large negative impact of temperature on slave exports. We also find a large negative effect if we use present-day countries as the unit of observation (not reported).

[21]These are available at `http://climate.geog.udel.edu/~climate/`.

3.3.4. *Outliers.* We discard statistical outliers, re-estimating the results using ordinary least squares (OLS), calculating dfbeta statistics, and then re-estimating the main tobit specification without observations whose absolute dfbeta is greater than $2/\sqrt{N}$.[22] Similarly, we show that we can achieve our main results without relying on certain subsets of the data. We eliminate the smaller ports in the sample by removing the bottom 50% of ports by total number of slaves exported. We also show that the results are not driven by inactive ports by excluding all observations from the data where a port has either ceased to export slaves, or has not yet begun its participation in the trade.

The results are not driven by any one region within Africa. We drop these regions one at a time. Though the effect is clearly largest for West-Central Africa, this can in part be accounted for by the region's overwhelming preponderance in the slave trade. Nunn (2008) estimates that Angola alone sent more than three and a half million slaves across the Atlantic between 1400 and 1900.

3.3.5. *Estimator.* We employ several alternative estimation strategies. We begin by re-estimating the main equation using OLS. The effect of a temperature shock remains negative and significant. Unsurprisingly, the estimated effect is smaller if we do not account for censoring. Using Conley (1999) standard errors and allowing spatial dependence over distances of up to 10 decimal degrees, the estimated standard error rises, but the result is still significant at the 5% level (not reported). We also find a significant and negative effect of temperature using a binary indicator for nonzero slave exports as the dependent variable, discarding observations with no slave exports, taking first-differences, or including lagged temperature as a control. The coefficient estimate remains large and negative if the running maximum of slave exports are included as a control; the same is true when including ten-year running means of temperature or its variance (not reported).

The number of observations is large relative to the number of fixed effects, and so the incidental parameters problem should only be a minor concern. However, because (1) is non-linear, Wooldridge (2002, p. 542) suggests including port-specific mean temperatures $\overline{temperature_i}$ rather than port fixed effects. Under the assumption that the port fixed effects δ_i are linearly related to the port-specific means ($\delta_i = \psi + a_i + \lambda\overline{temperature_i}$), this will give consistent estimates of β. The results are congruent with our baseline specification.

3.3.6. *Inclusion of lag slave exports.* We include lagged slave exports as a control. Since slave exports in the previous year are correlated with the error term, we use the difference between slaves exported two years ago and slaves exported three years ago as an instrumental variable for lagged slave exports. Although the coefficient estimate is

[22]The standard test of discarding high-leverage observations is not reported. Since no observations have leverage greater than $2(df + 1)/N$, these results are identical to the main specification.

smaller than in the baseline, the results again suggest a sizable reduction in slave exports during warmer years. Roughly 1,900 fewer slaves are exported per port in a year with a $1°\mathrm{C}$ rise in temperature.

Wooldridge (2005) suggests that censored models with a lagged dependent variable such as ours can be estimated by including lagged slave exports, mean temperature, and initial slave exports in the estimation. This is consistent under the assumption that the port-level fixed effects δ_i can be decomposed into $\delta_i = \psi + a_i + \lambda_1 slaves_{i0} + \gamma \overline{temperature_i}$. This decomposition assumes a relationship between the initial number of slaves from when the trade first started and the port-fixed characteristics and reduces it to a regular tobit estimation. Here too, warmer temperatures predict a sizeable reduction in slave exports, about 1,300 slaves per port in a year with a $1°\mathrm{C}$ temperature shock.

Re-estimating the same specification using the Arellano-Bond estimator (using two lags as an instrument), we find that the estimated coefficient on temperature is very similar to the estimate obtained using OLS. This is larger than the coefficient obtained by including the lagged dependent variable and estimating the effect using OLS. This suggests that, if there is any bias on the estimated coefficient on temperature when including the un-instrumented lag, it is towards zero, understating the effect of temperature on slave supply.

4. Interpretation

4.1. **Argument.** We argue that higher temperatures raised the cost of slave capture and export. Consider a coastal African ruler who maximizes profits from selling slaves, as in Fenoaltea (1999). The ruler "produces" a quantity S of slaves using an army that he controls. He may or may not be a price taker, and traders at the coast will pay $p(S)$ per slave. We assume the inverse demand function is downward-sloping: $p_s \leq 0$. The cost of raiding for S slaves is $C(S, T)$, where T is temperature. Costs are convex in both the quantity of slaves exported and in temperature. That is, $C_S > 0$, $C_{SS} > 0$, $C_T > 0$, and $C_{ST} > 0$. The ruler, then, will choose S to maximize $p(S)S - C(S, T)$. So long as demand is not "too convex,"[23] temperature reduces exports:

$$\frac{dS}{dT} = \frac{C_{ST}}{p_{ss}S + 2p_s - C_{SS}} < 0.$$

The critical assumption is that $C_{ST} > 0$. We believe this for four reasons. First, the ruler's costs of extracting tribute in order to feed a slave-harvesting army rise during bad harvests. Second, the mortality of slaves, soldiers and porters will rise in warmer years. In addition, with greater morbidity, the ruler's cost of providing slaves of any given quality will rise. Third, higher temperatures lead to greater evapotranspiration, increasing the probability that drought will set in. Areas of slave supply become more disordered, raising the costs of raiding directly. Finally, the slave trade depended on

[23] That is, $p_{ss}S + 2p_s - C_{SS} < 0$.

complementary economic activities that provisioned ships, fed the populations of the ports, and supplemented the incomes of slave traders.

4.2. **Temperature, agriculture, and mortality.** There is substantial evidence that temperature shocks affect agriculture and mortality in the present. Studies of the impact of climate on modern agricultural productivity in Africa (Kala et al., 2011; Kurukulasuriya and Mendelsohn, 2006) indicate that higher temperatures relative to the baseline climate have a negative impact on productivity, particularly for non-irrigated agriculture. In addition, higher temperatures increase evapotranspiration (Brinkman and Sombroek, 1996). This indicates that colder years lead to a relatively higher level of water availability for plants, which is crucial in certain stages of plant growth. Other studies of temperature impacts on the productivity of tropical agriculture find similar results (Guiteras, 2009; Sanghi and Mendelsohn, 2008) Thus, the link between colder years and higher agricultural productivity in the tropics is well established.

There is also evidence that higher temperatures increase disease burdens that raise mortality (Burgess et al., 2009). Studies of the relationship between disease and temperature find that higher temperatures are more conducive to the spread and transmission of diseases such as malaria and yellow fever (Alsop, 2007). Malaria and yellow fever have placed a particularly heavy mortality burden on Africa throughout the continent's history (Gallup and Sachs, 2001; Ngalamulume, 2004). Further, arid AEZs and modern-day child malnutrition are positively correlated (Sharma et al., 1996).

4.3. **Case studies.** In this section, we show that the histories of three major slave ports – Benguela, Whydah, and Mozambique – are consistent with our interpretation of our empirical findings. These three cases are selected as statistically influential ports that are well documented in the secondary literature and that come from three separate regions of the slave trade.[24] We show that, in each case, the slave trade was dependent on the health of the local agrarian economy.

4.3.1. *Benguela.* Benguela, in southern Angola, was founded in 1617 (Candido, 2006, p. 4). The town began its involvement in the slave trade by shipping slaves to Luanda for re-export (Candido, 2006, p. 4). After 1716, the legal requirement that ships sail to Luanda before leaving Angola was removed, and Benguela grew beyond the supervision of the Portuguese administration centered at Luanda (Candido, 2006, p. 22). Between 1695 and 1850, Candido (2006, p. 18) estimates that Benguela shipped nearly half a million slaves to the new world, making it the fourth most important port in the transatlantic trade, behind Luanda, Whydah, and Bonny. Though most of the slaves shipped through Benguela were Ovimbundu from the Western slopes of the highlands directly east of the

[24]In particular, if the main specification is estimated using OLS, the ten most influential ports by dfbeta are: Benguela, St. Paul De Loanda, Mozambique, Congo River, Ambriz, Cabinda, Whydah, Anomabu/Adja/Agga, Quilimane and Badagry. We chose our three ports from this list so that each case study that comes from a different region of Africa and is well documented in the secondary literature.

town (Curtin and Vansina, 1964, p. 189), these slaves were sold through a commercial network integrated with the one that served Luanda (Miller, 1989, p. 383).

War, abduction, tribute, debt, judicial enslavement, pawnship, sale of relatives, and self-enslavement were all important sources of the slaves sold at Benguela (Candido, 2006, p. 48). Warfare between local societies was seen as a legitimate method of enslavement, though this was difficult to distinguish from "illegal" methods such as kidnapping, which became more prevalent due to rising prices during the 1830s (Candido, 2006, p. 80). Judicial enslavement, similarly, only became a major source of captives in the mid-nineteenth century (Candido, 2006, p. 66).

Miller (1982, p. 29-30) argues that droughts, famines, and epidemics served to increase the supply of slaves from West-Central Africa through self-enslavement and a flow of refugees. We find, however, that slave exports are negatively correlated with adverse temperature shocks. There are two principal mechanisms for this in the case of Benguela. First, bad harvests created political disorder. Second, they disturbed activities complementary to the slave trade.

In West-Central Africa, droughts led to "violence, demographic dispersal, and emigration" (Miller, 1982, p. 32). Major confrontation between Portuguese forces and African states occurred with "suspicious regularity at the end of periods of significantly reduced precipitation" (Miller, 1982, p. 24). Tribute from local Sobas was often rendered in the form of slaves (Candido, 2006, p. 24), and disruption to this political order would have constricted the flow of slaves. Raids and famines both pushed Africans to resettle in more distant regions (Candido, 2006, p. 48), raising the costs of capture. The movement of villages in response to drought was so frequent in South-Central Africa that permanent dwellings were rarely built (Miller, 1996, p. 157).

The slave trade depended on the health of the local economy. African products, especially palm-cloth and salt, figured largely in the eighteenth century Angolan slave trade (Klein, 1972, p. 910). Portuguese soldiers in the interior were often without a regular salary, and so exchanged gunpowder inland for chickens and other agricultural products (Candido, 2006, p. 38). Military officials, similarly, had to buy food and other commodities using trade goods such as beads and textiles (Candido, 2006, p. 112). In addition to slaves, cattle, salt, ivory and shells were shipped from Benguela to Luanda in return for cassava flour. These were used to buy slaves and to supply ships (Candido, 2006, p. 24). Slaves held inland at Cacinda worked in agriculture to feed themselves and passing slave coffles. Their produce was also sent directly to Benguela (Candido, 2006, p. 213).

Luso-African traders working in the interior engaged directly in slave raids (Candido, 2006, p. 83). After the 1820s, slave exporters diversified increasingly into so-called "legitimate" goods (Candido, 2006, p. 112). Slaves were marched to the coast by caravan, and caravan porters used these as opportunities to trade on their own accounts (Candido, 2006, p. 124). Periods of higher temperatures, in addition to providing fewer trade opportunities, would have been times of greater mortality for both slaves and porters. The mortality of slaves between capture and the coast may have been over 50% in eighteenth-century Angola (Miller, 1996, p. 120).

4.3.2. *Whydah.* Whydah (or Ouidah), in southern Benin, was founded before the beginnings of European trade there in the seventeenth century (Law, 2004, p. 25). The town was brought under the control of Dahomey between 1727 and 1733, after which the volume of slaves exported declined (Law, 2004, p. 52-59). Despite the town's peculiar position 4 km inland, Whydah was Dahomey's principal port. It remained an important point of slave embarkation throughout the trade. Exports were between 8,000 and 9,000 persons annually during the 1750s, and some 4,500 per year circa 1788 (Law, 2004, p. 125-126). In the late 1700s, these were shipped mostly to Brazil and the French Caribbean (Law, 2004, p. 126).

The two principal sources of slaves traded through Whydah during the time period of this study were capture by the Dahomean army and purchase from the interior (Law, 2004, p. 138). Whydah fits the model closely, as the supply of slaves depended greatly on the local state's military strength. Dahomey competed with other states of the "Slave Coast" to supply slaves for the Atlantic trade. With the rise of Oyo in the late seventeenth century, the share of slaves shipped by Dahomey, and hence through Whydah, declined (Law, 2004, p. 126). Oyo attacks had made passage through Dahomey dangerous for slave suppliers (Ross, 1987, p. 369). After Dahomey's victory over Oyo in the early 1820s, she was free to launch campaigns in the Mahi and Yoruba countries to the north-east that increased slave exports through Whydah (Curtin and Vansina (1964, p. 190), Law (2004, p. 160)). During the 1750s, the king of Dahomey attempted to forcibly unify the Mahi polities in order to facilitate trade through the region (Law, 1989, p. 53). The Dahomean capture of Whydah itself appears to have been motivated by the state's desire to gain better access to the slave trade, and as its involvement grew the state became more militarized (Law, 1986, p. 247,258).

The early literature on Dahomey supposed, wrongly, that the slave trade was a royal monopoly. While this was not the case, captives brought by the king's army formed a substantial part of the trade (Law, 2004, p. 111). The state also enjoyed many special privileges, such as regulation of prices and the right to sell slaves first (Law, 2004, p. 129). Private middlemen supplemented this royal trade by purchasing them from neighboring countries (Law, 2004, p. 111). They became especially important once Dahomey became a significant port in the 1750s and 1760s (Law, 1989, p. 59). The ability to acquire slaves was tied to conditions in regions of slave supply; in the 1770s and 1780s, for example, disturbances on the coast made it difficult for Dahomey to buy slaves in eastern markets (Ross, 1987, p. 370).

This middleman trade also depended on the strength of the Dahomean army. It was the Dahomean conquest of alternative ports such as Jaquin and Apa that drove trade towards Whydah (Ross, 1987, p. 361). Strict military control over the movements of European traders living at Whydah kept the trade in Dahomean hands (Ross, 1987, p. 367). Though Dahomey abandoned its attempts to monopolize the trade of the slave coast after roughly 1750, it continued to attract trade by offering suppliers safer routes than through the surrounding country (Ross, 1987, p. 369).

The slave trade at Whydah did not exist separately from the local economy. The slave trade was supported by the local retail trade, agriculture, fishing and salt-making (Law, 2004, p. 77). Though Whydah's trade consisted mostly of slaves, other goods such as ivory, cotton, cloth and palm oil were also exported from the port (Law, 2004, p. 125). The city depended on goods imported from the interior that were consumed locally, including kola from Asante and natron from Borno (Law, 2004, p. 83). The earnings of private merchants were spent locally, while the trade itself depended on the labour of local porters, water-rollers, and laundry women, among other workers (Law, 2004, p. 147). Markets at Whydah sold a mix of local products and imported goods (Law, 2004, p. 148).

Because Europeans extended credit in the form of goods in return for the promise that slaves would be delivered at a future date, the trade depended on the conditions encountered by local merchants (Law, 2004, p. 133). Even before the Dahomean capture of Whydah, supply-side factors constrained the growth of slave exports. Law (1994, p. 82) reports that demand outpaced the Allada capacity to supply slaves in the 1630s, 1640s and 1670s, leading local merchants to become increasingly indebted to their Dutch buyers.

4.3.3. *Mozambique.* Though the Portuguese established a fort on Mozambique Island in 1508, the slave trade developed slowly in southeastern Africa due to the greater voyage lengths involved (Klein, 2010, p. 69). In the 1600s, Mozambique Island traded mostly in ivory (Newitt, 1995, p. 177). Mixed-race Afro-Portuguese settlers dominated trade along the Zambezi river until the nineteenth century, creating estates that functioned as miniature states complete with slave armies (Klein, 2010, p. 70). The slave trade that began to take off after 1750 was initially in French hands, and accelerated from the 1770s (Newitt, 1995, p. 245-6). Though interrupted by the Napoleonic Wars, the slave trade showed an upward trend until the 1830s. In the nineteenth century, Brazilian and Arab traders came to overshadow the French (Alpers, 1970, p. 84). There were four distinct markets for Mozambican slaves: French islands in the Indian Ocean, the Americas, the Portuguese East African possessions, and Madagascar (Newitt, 1972, p. 659).

Africans in the interior typically acquired female slaves through capture or purchase, while males were obtained through clientship arrangements that traded labor service for cattle or wives (Newitt, 1995, p. 234). Slaves exported from Mozambique were generated mostly among the Makua (Newitt, 1995, p. 247). Little is known about how this increased supply was provided. The only detailed contemporary account notes that caravans with trade goods would pass between settlements until a local chief was able to supply slaves. At that point, they would stop to establish a market (Newitt, 1995, p. 252).

Newitt (1995, p. 244) believes that it was the famines of the early nineteenth century that helped fill the slavers' barracoons. His argument focuses on the severe droughts that occurred from 1794 to 1802 and from 1823 to the late 1830s that are collectively referred to as the *mahlatule*. Local people normally responded to dry periods by intensifying other income-generating activities, such as hunting, gold mining and trading. When these too failed, they turned to out-migration, which led to instability, war, banditry and slaving (Newitt, 1995, p. 253). The long second drought upended peasant life, and much of the population starved, died of smallpox or moved elsewhere (Newitt, 1995, p. 254). The power of both the Afro-Portuguese and local African chieftaincies was undermined (Newitt, 1995, p. 254-55). Klein (2010, p. 71) expresses a similar view.

There are two problems with Newitt's (1995) interpretation. First, there is no control group. The first half of the nineteenth century was also a period of sustained Brazilian demand for slaves and British patrols that pushed trade towards West-Central and Southeastern Africa. Newitt does not test whether Mozambique exported more slaves during the *mahlatule* than would be expected given demand conditions. After 1811, Portugal allowed Brazilian ships to trade freely with its East African ports, reinforcing this greater demand (Klein, 2010, p. 72). Second, while drought produced disorder in Southeast Africa, it is not evident that this facilitated the supply of slaves. By disrupting settlement patterns, trading networks, and local states, droughts may have acted just as strongly to raise the costs of slaving. The Nguni states that were pushed north of the Zambezi by the *mahlatule* were known for their fierceness and economic self-sufficiency, both of which isolated the region from outside trade (Newitt, 1995, p. 264). The droughts similarly slowed Portuguese movement into the interior, and expansion by Afro-Portuguese along the Zambezi was only restored as peace returned in the 1850s and 1860s (Newitt, 1995, p. 264, 284). In addition, drought directly raised transportation costs by making rivers impassable (Newitt, 1995, p. 255).

As a military fortification, the island was dependent for its food from the mainland and neighboring islands (Newitt, 1995, p. 190). The island was often short on provisions (Alpers, 1970, p. 94). Ships engaging in the slave trade were similarly dependent on food and other supplies from local sources (Newitt, 1995, p. 249). French traders who visited the island also traded in rice, meat and cattle (Alpers, 1970, p. 94). These needs were keenly felt in periods of bad weather; the island was forced to import food during the drought in 1831 (Alpers, 2001, p. 77). As in the other cases studied, the functioning of the slave trade at Mozambique depended on complementary activities in the interior.

5. Conclusion

We find that environmental shocks within Africa influenced the dynamics of the slave trade. The effects we find are large. A temperature increase of one degree Celsius reduced annual exports by roughly 3,000 slaves per port. We interpret these as shifts in the cost of slave supply, operating through mortality and the productivity of complementary sectors. The histories of Benguela, Whydah, and Mozambique support our interpretation. Past temperature shocks predict economic activity today.

We have advanced the existing understanding of Africa's participation in the slave trade by incorporating previously unutilized, time-varying measures of weather shocks spanning all sending regions. This exercise demonstrates the importance of supply-side factors in the dynamics of the transatlantic slave trade. This has also enabled us to provide new evidence on the channels through which geography shapes economic development in a historical setting. We are able to examine the responsiveness of a different form of conflict to economic shocks than is typically studied in the literature. Rather than being encouraged by economic distress, slave raiding was hindered by it.

There are, of course, limitations of our approach. Data availability prevent us from looking at the dynamics of the Indian Ocean, Red Sea, or internal African slave trades. Similarly, we are unable to examine the period before 1730, or environmental factors other than temperature. Further, our results should not be over-interpreted; we can say little about the relative importance of the proposed mechanisms through which the link between temperature and the slave trade worked. Depending on their resource endowments and institutions, societies may adapt to change, particularly to slow-moving changes in climate. As climate scientists advance in their reconstruction of the environmental past, we are hopeful that it will become possible to examine further these issues and to better understand the long-run causes of Africa's poverty.

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APPENDIX A. KERNEL DENSITIES

FIGURE 2. Kernel densities of slave exports

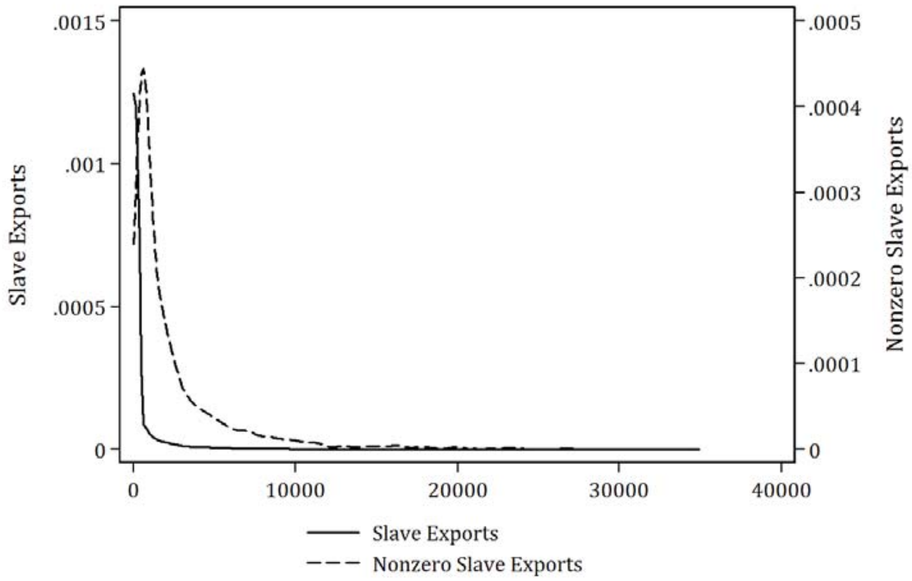
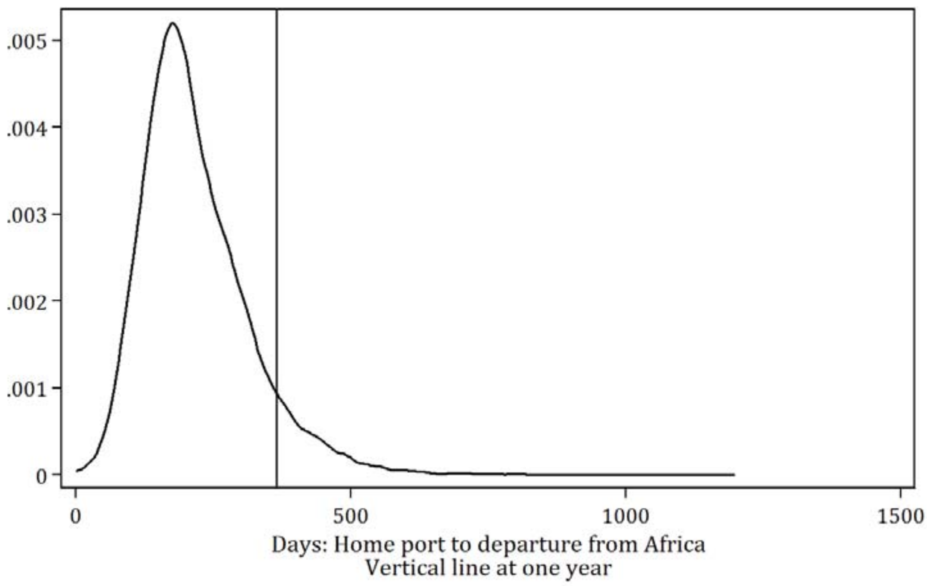


FIGURE 3. Kernel density of time to departure from Africa



APPENDIX B. MISSING DATA

We use the ship-level data to describe the variables that predict data quality in Table A5. We use whether the principal port of slave purchase is missing as an indicator of data quality. Without adding additional controls, it is clear that the data improve in quality from 1500 to 1550, before declining steadily to 1750. Data begin to improve again after 1750, only to become much worse after the suppression of the slave trade in the early 1800s. However, these trends are confounded by the changing composition of the slave trade over time, across national carriers, and regions of slave purchase. Relative to British ships, French and Portuguese carriers are less likely to lack data on the port of principal slave purchase. Controlling for time, however, reveals the Portuguese data to be of a lower quality. Relative to Southeast Africa, data from other regions, excepting the Gold Coast, tend to be of worse quality.

APPENDIX C. IMPACTS OF TEMPERATURE ON WIND SPEED

We use data from on modern temperature and wind speed from the NCC (NCEP Corrected by CRU) model, housed at the Laboratoire de Mtorologie Dynamique (Ngo-Duc et al., 2005). This is a global model at the 1° by 1° level, with observations available at 6-hourly intervals from 1948-2000 (We use the years 1950-2000). Ngo-Duc et al. prepare these data using satellite data as inputs into a global circulation model, correcting them using station-level data from the Climate Research Unit at East Anglia. Our regression specification is:

$$wind_{it} = \alpha + \beta temperature_{it} + point_i + year_t + \epsilon_{it},$$

where $wind_{it}$ and $temperature_{it}$ is the mean annual wind speed in m/s and mean annual temperature in degrees Celsius at point i in year t, respectively, $point_i$ is the point fixed effect, and $year_t$ is the year fixed effect. We run this specification both at the global level, and for the region around Africa (which restricts latitude to between -50 and 50 and longitude to between -40 and 60).

Table 1: Summary statistics

	(1) Mean	(2) s.d.	(3) Min	(4) Max	(5) N
Slaves exported	444	1,813	0	34,927	18,358
Slaves (non-zero)	2,543	3,673	1.23	34,927	3,206
Temperature (interpolated)	25.2	2.33	13.3	27.5	18,358
Temperature (closest point)	25.2	2.34	13.3	27.4	18,358
Climate (30 year mean temperature)	25.2	2.32	13.4	27.3	18,224
Deviation from 30 year mean temperature	-0.00043	0.13	-0.86	0.62	18,224
Year	1,798	39.5	1,730	1,866	18,358
AEZ: Desert	0.030	0.17	0	1	18,358
AEZ: Subhumid	0.28	0.45	0	1	18,358
AEZ: Forest	0.43	0.50	0	1	18,358
AEZ: Dry Savannah	0.15	0.36	0	1	18,358
AEZ: Moist Savannah	0.11	0.32	0	1	18,358

Table 2: Main results

	(1)
Temperature	-3,052.036***
	(589.096)
Year F.E.	Y
Port F.E.	Y
Observations	18,358
Standard errors clustered by	
Year †	(786.560)
Artificial square †	(633.235)

Notes: ***Significant at 1%, **Significant at 5%, *Significant at 10%. Standard errors clustered by closest climate point X year in parentheses. The dependent variable is slave exports. All regressions are tobit. † Anomaly used in place of temperature.

Table 3: Results by agro-ecological zone

	(1)	*Tests for equality of coefficients: p-values*			
Temperature X		Desert	Dry Savannah	Sub-humid	Moist Savannah
Desert	-3,862.479**				
	(1,888.139)				
Dry Savannah	-3,924.739***	0.97			
	(706.096)				
Sub-humid	-2,643.011***	0.53	0.18		
	(863.810)				
Moist Savannah	-1,570.826*	0.24	0.01	0.28	
	(801.907)				
Humid forest	239.193	0.03	0.00	0.01	0.06
	(946.407)				
Year F.E.	Y				
Port F.E.	Y				
Obs.	18,358				

Notes: ***Significant at 1%, **Significant at 5%, *Significant at 10%. Standard errors clustered by closest climate point X year in parentheses. The dependent variable is slave exports. All regressions are tobit. † Anomaly used in place of temperature.

Table 4: Climate

	(1)	(2)	(3)
Deviation from temperature normal	-1,244.226**		-2,640.017***
	(573.612)		(542.358)
Temperature normal		-18,583.692***	-20,727.432***
		(1,726.335)	(1,760.309)
Year F.E.	Y	Y	Y
Port F.E.	Y	Y	Y
Obs.	18,224	18,224	18,224

Notes: ***Significant at 1%, **Significant at 5%, *Significant at 10%. Standard errors clustered by closest climate point X year in parentheses. The dependent variable is slave exports. All regressions are tobit. † Anomaly used in place of temperature.

Table 5. The modern impact of past temperature anomalies

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Anomaly	0.004**	0.004**	0.065***	0.050***	0.139***	0.059**	0.166***	0.050***
	(0.002)	(0.002)	(0.022)	(0.019)	(0.050)	(0.027)	(0.045)	(0.017)
Controls	N	Y	Y	Y	Y	Y	Y	Y
Time Period	All	All	1730s	1740s	1750s	1760s	1770s	1780s
Obs.	134	134	134	134	134	134	134	134
R2	0.061	0.466	0.482	0.478	0.484	0.464	0.500	0.480
	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
Anomaly	0.037**	0.050**	0.019	0.036	0.044*	0.031*	0.035*	0.047*
	(0.018)	(0.023)	(0.026)	(0.033)	(0.026)	(0.018)	(0.020)	(0.028)
Controls	N	Y	Y	Y	Y	Y	Y	Y
Time Period	1790s	1800s	1810s	1820s	1830s	1840s	1850s	1860s
Obs.	134	134	134	134	134	134	134	134
R2	0.465	0.474	0.444	0.449	0.458	0.456	0.461	0.459

Notes: ***Significant at 1%, **Significant at 5%, *Significant at 10%. Robust standard errors in parentheses. All regressions are OLS. The dependent variable is log light density. All regressions include a constant. Controls are absolute latitude, longitude, the number of raster light density points within 500km of the port, dummies for AEZs, distance from the nearest Atlantic or Indian Ocean port of slave demand, and average temperature over the period 1902-1980.

Table A1: Robustness checks 1

Heterogeneity		Measurement	
Linear port trends	-1,679.178***	*Known slaves*	-1,848.224***
	(526.206)		(431.109)
Obs.	18,358	Obs.	18,358
Quadratic region trends †	-1,704.436***	*Known slaves + Region known*	-2,132.068***
	(551.482)		(442.958)
Obs.	18,358	Obs.	18,358
Pre-1807	-2,145.903***	*Closest temperature point*	-2,629.372***
	(517.928)		(511.774)
Obs.	10,318	Obs.	18,358
Post-1806	-2,191.991**	*Temperature: Ethnicities within 500 km*	-2,488.260***
	(938.333)		(496.954)
Obs.	8,040	Obs.	17,243
		Outliers	
Active ports only †	-2,307.077***	*No high dfbeta*	-2,019.501***
	(598.568)		(343.458)
Obs.	6,780	Obs.	17,816
Control for New World Temperature	-3,090.307***	*Top 50% of ports*	-3,288.915***
	(590.740)		(623.347)
Obs.	18,358	Obs.	9,179
Control for prices	-2,235.815***	*Top 50% of years by port*	-1,885.926***
	(490.882)		(529.963)
Obs.	10,854	Obs.	9,246
		Level of observation	
Temperature shock at modal destination	-3,315.004***	*Artificial squares (1x1)*	-3,185.097***
	(549.055)		(622.382)
Obs.	17,536	Obs.	16,166
Including Temperature X Bovines	-4,189.407***	*Artificial squares (5x5)*	-5,524.228***
	(820.794)		(1,317.865)
Obs.	18,358	Obs.	3,836
Including Temperature X Husbandry	-3,713.246***	*Region-level*	-11,394.601***
	(1,253.220)		(3,624.518)
Obs.	18,358	Obs.	1,096
Including Temperature X Tsetse Suitability	-4,420.347***		
	(1,015.151)		
Obs.	17,536		

Notes: ***Significant at 1%, **Significant at 5%, *Significant at 10%. Standard errors clustered by closest climate point X year in parentheses. The dependent variable is slave exports. All regressions are tobitwith port and year fixed effects unless otherwise indicated. † Anomaly used in place of temperature.

Table A2: Robustness checks 2

Estimation		*Including lag slave exports*	
OLS	-576.496***	*Include lag slaves*	-1,858.184***
	(171.082)		(373.904)
Obs.	18,358	Obs.	18,224
Dependent variable: Any slaves (OLS)	-0.064**	*Instrument for lag slaves with lag difference*	-1,933.029***
	(0.028)		(377.417)
Obs.	18,358	Obs.	18,090
No zeroes (OLS)	-2,582.865***	*Port mean anomaly, year F.E., lag slave exports, and initial slave exports*	-1,340.182***
	(635.856)		(373.090)
Obs.	3,206	Obs.	18,224
First differences (OLS)	-297.136***	*OLS with lag*	-387.113***
	(82.540)		(108.378)
Obs.	18,224	Obs.	18,224
Port mean anomaly	-2,397.329**	*Arellano-Bond* ‡	-613.994*
	(1,108.037)		(345.046)
Obs.	18,358	Obs.	18,090
Include lag temperature	-2,297.635***		
	(610.195)		
Obs.	18,224		

Notes: ***Significant at 1%, **Significant at 5%, *Significant at 10%. Standard errors clustered by closest climate point X year in parentheses. The dependent variable is slave exports. All regressions are tobit with port and year fixed effects unless otherwise indicated. † Anomaly used in place of temperature. ‡ Robust, rather than clustered, standard errors reported.

Table A3: Results with specific regions removed

	(1)	(2)	(3)	(4)
Temperature	-4,027.456***	-3,360.568***	-3,119.462***	-2,784.236***
	(750.302)	(609.768)	(597.464)	(578.477)
Year F.E.	Y	Y	Y	Y
Port F.E.	Y	Y	Y	Y
Obs.	16,166	16,577	15,344	16,714
Removed	Senegambia	Sierra Leone	Windward	Gold Coast

	(5)	(6)	(7)	(8)
Temperature	-3,006.031***	-3,453.181***	-994.467*	-3,166.473***
	(597.231)	(627.069)	(521.718)	(654.363)
Year F.E.	Y	Y	Y	Y
Port F.E.	Y	Y	Y	Y
Obs.	15,892	15,755	15,755	16,303
Removed	Benin	Biafra	West-Central	Southeast

Notes: ***Significant at 1%, **Significant at 5%, *Significant at 10%. Standard errors clustered by closest climate point X year in parentheses. The dependent variable is slave exports. All regressions are tobit with port and year fixed effects.

Table A4: Temperature correlations over space: 1980-2000

	(1)
Temperature at point *j* X point is within:	
200 km to 300 km	0.654***
	(0.011)
300 km to 400 km	0.553***
	(0.004)
400 km to 500 km	0.486***
	(0.005)
500 km to 600 km	0.513***
	(0.015)
600 km to 700 km	0.384***
	(0.005)
700 km to 800 km	0.334***
	(0.004)
800 km to 900 km	0.388***
	(0.010)
900 km to 1000 km	0.285***
	(0.005)
1000 km to 1100 km	0.201***
	(0.005)
1100 km to 1200 km	0.213***
	(0.004)
1200 km to 1300 km	0.201***
	(0.007)
1300 km to 1400 km	0.122***
	(0.003)
1400 km to 1500 km	0.095***
	(0.004)
1500 km to 1600 km	0.170***
	(0.007)
1600 km to 1700 km	0.056***
	(0.003)
1700 km to 1800 km	0.048***
	(0.005)
1800 km to 1900 km	0.073***
	(0.005)
1900 km to 2000 km	0.055***
	(0.004)
Pair *(i,j)* FE	Y
Year FE	Y
Observations	2,332,440

Notes: ***Significant at 1%, **Significant at 5%, *Significant at 10%. Robust standard errors in parentheses. The dependent variable is temperature. The estimator is OLS.

Table A5: Predictors of missing data

	(1)	(2)	(3)	(4)
(Year-1500) X (1500 to 1550)	-0.008***			-0.005***
	(0.000)			(0.000)
(Year-1550) X (1550 to 1600)	0.002***			-0.003***
	(0.001)			(0.000)
(Year-1600) X (1600 to 1650)	0.000			0.001***
	(0.001)			(0.001)
(Year-1650) X (1650 to 1700)	0.003***			0.002***
	(0.000)			(0.000)
(Year-1700) X (1700 to 1750)	0.003***			-0.000
	(0.000)			(0.000)
(Year-1750) X (1750 to 1800)	-0.003***			-0.002***
	(0.000)			(0.000)
(Year-1800) X (1800 to 1850)	0.003***			-0.003***
	(0.000)			(0.000)
(Year-1850) X (1850 to 1900)	0.039***			-0.015***
	(0.002)			(0.001)
Registered: France		-0.125***		-0.062***
		(0.008)		(0.005)
Registered: Portugal		-0.081***		0.059***
		(0.008)		(0.007)
Registered: Other		0.152***		0.146***
		(0.006)		(0.005)
Region: Senegambia			-0.008	0.014
			(0.012)	(0.013)
Region: Windward			-0.048***	-0.001
			(0.013)	(0.014)
Region: Sierra Leone			0.107***	0.162***
			(0.017)	(0.018)
Region: Gold Coast			-0.051***	-0.043***
			(0.012)	(0.012)
Region: Bight of Benin			0.219***	0.216***
			(0.013)	(0.013)
Region: Bight of Biafra			0.040***	0.090***
			(0.012)	(0.013)
Region: West-Central Africa			0.074***	0.073***
			(0.011)	(0.012)
Region: Missing			0.883***	0.895***
			(0.011)	(0.011)
Region: Other			0.475***	0.471***
			(0.017)	(0.017)
Observations	34,948	34,948	34,948	34,948

Notes: ***Significant at 1%, **Significant at 5%, *Significant at 10%. Robust standard errors in parentheses. The dependent variable is a dummy for whether the major port of slave purchase is missing. All regressions are OLS.