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 the cost of supplying slaves. Our results help explain African participation in the slave trade, which is associated with adverse outcomes today. We merge annual data on African temperatures with a panel of port-level slave exports to show that a typical port exported fewer slaves in a year when the local temperature was warmer than normal. This result is strongest where African ecosystems are least resilient to climate change, and is robust to several alternative specifications and robustness checks. We support our interpretation using evidence from the histories of Whydah, Benguela, and Mozambique.

1. INTRODUCTION

Africa's lack of consistent growth has been attributed to many causes, including the continent's geography, its institutions, and its ethnic divisions (Bloom and Sachs, 1998; Collier and Gunning, 1999; Easterly and Levine, 1997). The slave trades, in particular, are 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, 2010), 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 (2008) uses shifts in the demand for slaves to estimate a supply curve in Africa's guns-for-slaves cycle. His is the only empirical study of African supply dynamics of which we are aware, and he focuses on demand-side fluctuations. Our focus is on supply-side environmental shocks. Historians such as Hartwig (1979), Miller (1982), and Newitt (1995) have suggested that droughts and famines may have either increased or decreased the supply of slaves. Crises pushed people to sell

†UNIVERSITY OF OXFORD
*YALE UNIVERSITY
E-mail addresses: james.fenske@economics.ox.ac.uk, namrata.kala@yale.edu.
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themselves or their dependants into slavery, but also led to death and dispersion that reduced the availability of slaves for export. 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 results, estimating the impact of port-specific annual temperature fluctuations on slave exports.

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 combine this data 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 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 $1°\text{C}$ 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, and higher 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.

Our results help explain the relationship between the environment and development. Powerful arguments have been advanced linking geography to economic growth (e.g. Bloom and Sachs (1998); Engerman and Sokoloff (1997)). 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.,

[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).

2001; Fenske, 2010). 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 to uncover the burdens imposed by geography (Bleakley, 2007; Cutler et al., 2010). Studies that have used variation over time in temperature and rainfall have shown that these changes affect development both over the short run (Dell et al., 2011; Jia, 2011) and over the course of centuries (Vlassopoulos et al., 2009). The mechanisms for these effects are not yet fully understood. We provide 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. The slave trade's effects on modern-day institutions, mistrust and and poverty in Africa are in part a reflection of the continent's environmental history.

We also add to the existing knowledge on the economics of conflict. Strong correlations between economic shocks, economic grievances, and the onset of conflict have been asserted in the literature (Collier and Hoeffler, 2004; 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, 2008), while Japan's long recession has cut into the *yakuza's* profits from racketeering (Hill, 2006, p. 247). 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.

Finally, we contribute to the literature on the economics of climate change. Existing studies of the importance of historical climate change have focused largely on the impacts of abrupt and persistent changes on the collapse of civilizations through lowered agricultural productivity, depopulation, the decline of cities and the weakening of states (DeMenocal et al., 2001; Haug et al., 2003; Weiss and Bradley, 2001). We provide evidence that even small, short-run changes had large impacts on the productive sectors and coping mechanisms of African societies. As the slave trade shaped institutions in Africa, these effects will persist into the present.

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. 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. DATA AND EMPIRICAL STRATEGY

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 censored at 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. 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. 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.** 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 used a variety of proxy climate indicators, combining data from several previous paleoclimatic studies that calculated historical temperatures using data from different proxy indicators of temperature. These include coral, ice cores, tree rings, and other long instrumental records. These anomalies are reported for each year from 1730 to 1900, and are computed relative to the baseline average temperature during the period 1902 to 1980. A temperature anomaly of $1°\mathrm{C}$ at port i in year t means that the temperature at i was $1°\mathrm{C}$ higher during t than the mean temperature at i over the period 1902-1980. We also use a separate temperature series from the University of Delaware, which covers the 1902-1980 period. This allows us to reconstruct the baseline temperatures for each port, permitting us to convert the anomalies into an annual temperature series for each port.[2]

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 observation. 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.

The second source of data that we use is the Trans-Atlantic Slave Trade Database of Eltis et al. (1999).[3] The trans-Atlantic slave trade, which is the focus of this study, comprised roughly 65% 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.[4] We assign slaves from ships from known regions and unknown ports in proportion to 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 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. 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

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[2]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, but we are willing to provide the data on request.

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

[4]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.

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 about 0.16. We include a brief description of the impacts of a one standard deviation increase in temperature in section 3.

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 zone, and humid forest.

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 each port on average. 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 $0.16°\mathrm{C}$), the effect would be about 480 slaves.[5] This is roughly a one quarter of a standard deviation movement in slave exports.

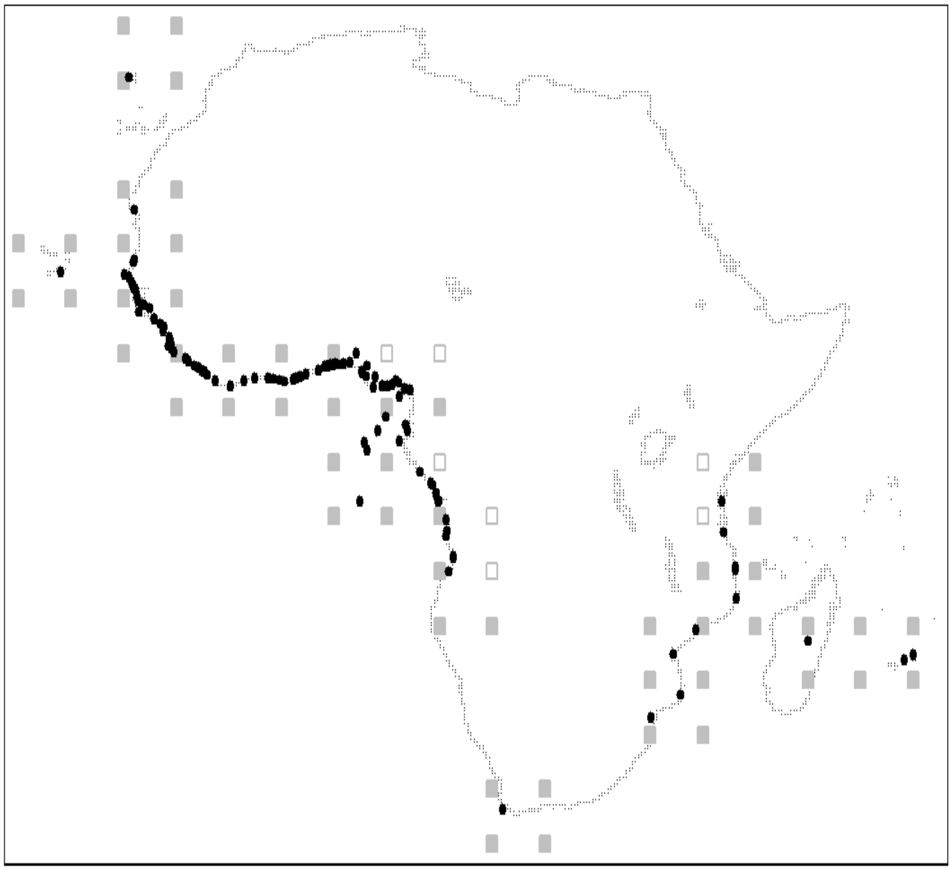
3.2. **Mechanisms.**

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. These are the regions in which agriculture would be most sensitive to fluctuations in weather. 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

[5]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.

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). 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. *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.[6] 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, this is very significant. Though this is a large elasticity, temperature shocks explain less than 1% of the variance in rainfall fluctuations.[7] 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.[8]

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

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

[7]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.

[8]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.

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.

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. Note that, 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.

3.3.1. *Heterogeneity.* To account for port-specific heterogeneity, we have allowed for port-specific linear trends and region-specific quadratic trends.[9]

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 slave prices, both in the embarkation region and in the nearest new world port.[10] 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.

[9]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.

[10]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.

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. 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.

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.

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 $2/\sqrt{N}$.[11] 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.

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

[11]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.

account for censoring. 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 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 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 $1°\text{C}$ 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 $1°\text{C}$ 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 is a price taker, and traders at the coast will pay p per slave. The ruler "produces" a quantity S of slaves using an army that he controls. 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 $pS - C(S,T)$. Temperature, then, reduces exports:

$$\frac{dS}{dT} = -\frac{C_{ST}}{C_{SS}} < 0.$$

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. 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 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. 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 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 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.

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.

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 to 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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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
Temperature normal	25.2	2.32	13.4	27.3	18,224
Deviation from temperature normal	-0.00055	0.14	-0.86	0.73	18,224
Year	1798	39.5	1730	1866	18,495
AEZ: Desert	0.045	0.21	0	1	18,358
AEZ: Subhumid	0.27	0.44	0	1	18,358
AEZ: Forest	0.43	0.49	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	-3,048.419***
	(585.262)
Year F.E.	Y
Port F.E.	Y
Observations	18,358
Standard errors clustered by	
Port †	(647.599)
Artificial square †	(610.549)

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	-4,497.155**					
	(1,877.538)					
Dry Savannah	-3,923.356***	Dry Savannah	0.77			
	(705.245)					
Sub-humid	-2,559.948***	Sub-humid	0.32	0.16		
	(863.288)					
Moist Savannah	-1,560.011*	Moist Savannah	0.13	0.01	0.31	
	(800.021)					
Humid forest	238.379	Humid forest	0.01	0.00	0.01	0.06
	(942.946)					
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	-1,267.362**		-2,658.416***
	(569.794)		(539.651)
Temperature normal		-18,460.958***	-20,628.291***
		(1,720.199)	(1,754.883)
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 A1: Robustness checks 1

<u>*Heterogeneity*</u>		<u>*Measurement*</u>	
Linear port trends	-1,683.249***	*Known slaves*	-1,848.411***
	(524.118)		(427.755)
Obs.	18,358	Obs.	18,358
Quadratic region trends †	-1,708.808***	*Known slaves + Region known*	-2,131.973***
	(548.612)		(440.114)
Obs.	18,358	Obs.	18,358
Pre-1807	-2,127.189***	*Closest temperature point*	-2,636.976***
	(514.927)		(508.351)
Obs.	10,318	Obs.	18,358
Post-1806	-2,191.992**	<u>*Level of observation*</u>	
	(938.323)	*Artificial squares (1x1)*	-3,178.098***
Obs.	8,040		(617.853)
		Obs.	16,166
Active ports only †	-2,315.232***		
	(595.612)	*Artificial squares (5x5)*	-5,519.570***
Obs.	6,780		(1,307.552)
		Obs.	3,973
Control for New World Temperature	-3,086.413***		
	(586.896)	*Region-level*	-11,203.841***
Obs.	18,358		(3,561.971)
		Obs.	1,096
Control for New World Prices	-2,222.808***		
	(488.278)	<u>*Outliers*</u>	
Obs.	10,854	*No high dfbeta*	-1,979.578***
			(342.342)
Temperature shock at modal destination	-3,290.472***	Obs.	17,826
	(546.155)		
Obs.	17,536	*Top 50% of ports*	-3,283.250***
			(618.649)
		Obs.	9,179
		Top 50% of years by port	-1,893.247***
			(525.018)
		Obs.	9,246

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	-547.780***	*Include lag slaves*	-1,867.285***
	(161.446)		(372.145)
Obs.	18,358	Obs.	18,224
Dependent variable: Any slaves (OLS)	-0.063**	*Instrument for lag slaves with lag difference*	-1,939.343***
	(0.027)		(375.234)
Obs.	18,358	Obs.	18,090
No zeroes (OLS)	-2,575.102***	*Port mean anomaly, year F.E., lag slave exports, and initial slave exports*	-1,311.923***
	(632.738)		(361.013)
Obs.	3,206	Obs.	18,224
First differences (OLS)	-279.332***	*OLS with lag*	-366.597***
	(77.961)		(102.543)
Obs.	18,224	Obs.	18,224
Port mean anomaly	-2,340.794**	*Arellano-Bond* ‡	-577.383*
	(1,062.312)		(325.843)
Obs.	18,358	Obs.	18,090
Include lag temperature	-2,310.143***		
	(606.366)		
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	-4,024.294***	-3,356.947***	-3,113.533***	-2,784.235***
	(745.177)	(606.034)	(593.385)	(578.474)
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	-3,003.122***	-3,445.559***	-1,010.034**	-3,163.152***
	(593.142)	(622.585)	(512.305)	(649.531)
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.