Technological Improvement and Climate Change Mitigation: Evidence from the Diffusion of Air Conditioning and Seasonal Mortality in the US*

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Abstract

This paper examines how the spread of residential air conditioning since the second half of the 20th century has changed the relationship between weather and mortality in the United States. Air conditioning reduces mortality in two ways: (1) it mitigates the adverse effect of extreme weather on health, even in the absence of any induced-migration (a partial equilibrium effect), and (2) it increases geographical mobility (a general equilibrium effect). Exploiting within-county fluctuation in weather over time and the changes in air-conditioning prevalence due to secular decline in the cost of air-conditioning, we show that higher air conditioning prevalence is associated with lower all-cause mortality rates. The health benefit derived from air conditioning is more significant in urban counties and among the older population. In particular, air conditioning reduces mortality most significantly from cardiovascular and respiratory diseases. We find that a 10% increase in air conditioning prevalence is associated with 5 fewer deaths per 100,000.

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1. Introduction

According to a recent report published in the leading medical journal the Lancet, climate change is the biggest global health threat of the 21st century (Costello et al., 2009). For instance, it is claimed that rising temperatures are likely to generate heat-related stress and to increase the short-term mortality rate due to heatstroke. This report, also known as "the Stern report for medics," highlights the health care infrastructure cost of *adaptation* to a warmer world and the consequences of climate-related mass *migrations* as key policy concerns. Adaptation is indeed unavoidable because even the most stringent mitigation efforts cannot avoid further impacts of climate change in the next few decades (IPCC Fourth Assessment Report, 2007). However, until recently, policy debate had been concentrated mostly on mitigation, partly because mitigation calls for a great deal of collective action that may warrant more aggressive government intervention.

Most methods of adaptation involve some form of technology. Unlike mitigation, which is a relatively new task, adaptation is generally a continuation of an ongoing process, and hence statistical causal inference from historical data is feasible. Moreover, compared with mitigation, adaptation tends to be dispersed across all socioeconomic sectors, and hence market forces are likely to play a more important role. In this paper, we focus on one technology for adaptation to climate change — air conditioning. The post-war era in the United States saw the transformation of residential air conditioning from a pure luxury to a common feature of American life driven by a secular decline in the price of air conditioners, and air conditioning is said to affect the pace of the postwar economic and social development in the American South. This paper investigates how the spread of residential air conditioning since the second half of the 20th century has changed the relationship between weather and mortality in the United States.

While the impact of air conditioning impact on mortality from heat may be of primary interest in the wake of global warming,[1] this technology affects health through several channels. It does directly affect health by offering protection from heat. It provides ventilation and humidity control, which could inhibit the proliferation of some types of microorganisms. It can be used to filtrate and disinfect the air but it can also promote the growth and spread of microorganisms if not maintained appropriately. The actual effect on air cleanliness thus depends on how it is commonly used.

In addition it generates behavioral responses. By increasing intra-household amenities, air conditioning affects people's incentives of spending time outside and could lead to a more sedentary lifestyle, a known determinant of cardiovascular disease. On the other hand a reduction in the time spent outside reduces exposure to vector-borne diseases.

Second, there is no doubt that the development of air conditioning has made the South and the Sunbelt in general more attractive places to live. To the extent that population growth in these warmer places has been driven by the improved consumer amenities due to the decline in the cost of air conditioning, air conditioning has an impact on mortality by increasing geographical mobility and reducing migrants' exposure to cold days (a general equilibrium effect). In environmental economics, counterfactual analysis based on partial equilibrium analysis may lead to misleading conclusions when general equilibrium effects are important (Sieg, et al. 2004). We use data over time covering three decades, allowing us to account for general equilibrium effects.

[1] Most, if not all, recent discussion of the health impact of global warming change has been focusing on its potential adverse consequences (see Patz, et al 2005 for a recent review). Langford and Bentham (1995) is one exception.

Our starting point is the previous epidemiology literature. This strand of literature investigates the impact of air conditioning on heat related mortality and is based on some recent evidence from a few cities (see the next section), a strategy that has significant caveats. The diffusion of air conditioning in the United States was almost complete by 1990. Conditioning on weather, therefore, the cross-sectional variation in air conditioning prevalence tends to be driven by socioeconomics as well as health factors, which are correlated with mortality. These problems might explain the lack of a significant relationship between room air-conditioning and mortality in hot weather (O'Neill et al., 2005; Rogot et al., 1992).

Thanks to technological improvement, the price of room air conditioners in the United States fell by more than half over the 1960-1980 period (Gordon, 1990), while the proportion of housing units with room air conditioners increased from slightly more than 10 percent to almost 30 percent. The increase in the prevalence of central air conditioners was even more significant: from 2 percent in 1960 to 30 percent in 1980 (Census of Housing). This study uses this sharp time-series variation in air-conditioning prevalence to estimate the impact of air conditioning on the temperature-mortality relationship.

More precisely, by conditioning on the county-by-month and state-by-year fixed effects, as well as county-by-month-specific trends, we exploit within-county changes in air conditioners prevalence over the 1960-1980 period instead of cross-sectional differences across counties. When the sharp increase in air conditioning prevalence over our sample period is driven predominantly by the decline in the cost of air conditioner, which is orthogonal to unobserved determinants of mortality rates after controlling for their trends, our fixed effects estimates identify the extent to which air conditioning protects Americans from heat-related deaths.

While the fixed effects estimation is useful in removing the county-specific influence of determinants of both air-conditioning prevalence and mortality, it does not necessarily identify the causal effect of air conditioning, because its adoption may also depend on factors other than its price, and these factors may be correlated with heath. For instance, if those who are more vulnerable (e.g. the sick and the elderly) are more likely to have residential air conditioning to protect themselves against heat stress, our fixed effects estimates can be considered to be the lower bound values of the health benefit of air conditioning.

Our second strategy is to use instrumental-variable method. During this period price changes were driven by technological progress (Biddle, 2008). In 1951 efficient, inexpensive window unit air conditioning hit the United States market (Arsenault, 1984). The adoption rate appears to be relatively fast even in the beginning because air conditioning prevalence was already slightly more than 10 percent in 1960. Between 1960 and 1980 the price of air conditioning dropped by more than half leading to a rapid increase in air conditioning prevalence — the number of households with air conditioning tripled. Thus variation in price should be correlated with air conditioning prevalence but not health outcomes, making price a plausible instrument.

The results from our IV estimation show that higher air conditioning prevalence is associated with lower all-cause mortality rate in hot weather. The typical person in this sample experiences an average of 2 days per month of temperatures over 80°F, the equivalent of approximately 6.7 percent of the entire month. Our results indicate that in such typical month having an additional 10 percent of occupied houses equipped with air conditioning is associated with 0.4 fewer deaths per 100,000. When we classify counties into urban and rural ones and re-estimate our model in each subsample, we find that the air conditioning-mortality relationship is larger in urban counties. This finding is in contrast to Burgess et al.'s (2009) result that extreme weather has adverse health impact in rural but not urban India. In addition, we find some evidence that the older population is more vulnerable to heat waves and they also derive more health benefits from air conditioning. Finally, when we examine the effect on different causes of death, our fixed-effects results show that air conditioning reduces mortality most significantly from cardiovascular diseases and respiratory disease among the female population.

2. Background

A. Extreme Weather and Mortality

The influence of seasons and temperature in particular on mortality has been documented since the mid-19th century (Guy and Cantab, 1843). More recently, the Stern report for medics claims that heat has a major effect on mortality even today, with the 2003 European heat wave causing up to 70,000 excess deaths. Results from the recent literature, however, cast considerable doubt on the relationship between extreme heat and mortality, because much of the excess mortality on hot days is simply "harvesting", which refers to a brief temporal advancement of death among persons who are already ill or frail and at high risk of dying. The extensive literature on the relationship between extreme temperature and mortality is well summarized by Deschênes and Moretti (2009). [2]

Consistent with the epidemiology literature (e.g. Basu and Samet, 2002), Deschênes and Moretti find that the increase in mortality following extreme heat appears to be mostly driven by near-term displacement. However, the increase in mortality following extreme cold is not merely "harvesting;" the deaths attributable to cold weather imply significant reduction in life expectancy. Deschênes and Moretti also estimate that a nontrivial fraction of the gain in

[2] See also Rau (2006). Indeed, according to Rau, the relationship between weather and mortality was perhaps first noticed by Hippocrates in his "Airs, Waters and Places" almost 2,500 years ago.

longevity experienced by the United States population over the past thirty years can be attributed to internal migration from the colder northeastern and midwestern states to the warmer southwestern states. This is an interesting finding, although the paper does not attempt to explain the observed migration pattern.

The finding that extreme heat has little effect on mortality in the United States perhaps can be explained by protection against high temperatures via adaptation. Deschênes and Greenstone (2011) conjecture that individuals' likely first compensatory response to extreme heat is increased use of air conditioning.[3] They find that residential energy consumption is highest on cold and hot days, which is consistent with their adaptation hypothesis. Based on these findings, they infer that the mortality impacts would be larger without the increased energy consumption. Indeed, by conducting a similar exercise using data from India, Burgess et al. (2009) show that the impact of extreme heat on mortality is quite dramatic, especially in rural areas with higher poverty rates and higher dependence on agriculture for income and employment. While both of these studies point to adaptation through air conditioning, none of them directly examines the impact of the prevalence of air conditioning on mortality.

The literature found evidence that links humidity and health. Low humidity is associated with the spread of airborne diseases (Lowen et al. 2007; Shaman and Kohn 2009; Xie et al. 2007). At the same time high humidity has been found to encourage the spread of bacteria and fungi (Baughman and Arens 1996). Consistent with these results, more recently Barreca (2001) finds a U-shaped relationship between humidity and mortality from all causes.

B. Air Conditioning and Mortality

[3] According to the Centers for Disease Control and Prevention (CDC), air conditioning is the number one protective factor against heat-related illness and death.

A small number of papers from the epidemiology literature have investigated the potential benefit of air conditioning in reducing heat-related deaths. Kilbourne et al. (1982) observe an inverse association between daily hours of home air conditioning and heatstroke in St Louis and Kansas City during the summer of 1980. By contrast, O'Neill et al. (2005) report that between 1986 and 1993 heat-related mortality in four cities (Chicago, Detroit, Minneapolis, and Pittsburgh) was not related to room-unit air-conditioning prevalence, although the heat-related mortality decreased as central air-conditioning prevalence increased. In addition, O'Neill et al. argue that central air-conditioning prevalence explained some of the differences in heat effects by race. However, these studies are not nationally representative so it is not obvious their results are generalizable. In addition, none of these studies systematically considered the confounding effects from income and education, which may explain the lack of health benefit from room-unit air-conditioning.

Rogot et al. (1992) provide the first large-scale analysis of the relationship between air conditioning and mortality in hot weather. Using 1980 census data on air-conditioning prevalence, Rogot et al. also find that there is no health benefit derived from room air conditioning. However, they report that the death rate in hot weather for persons in households with central air conditioning was lower than for persons in households without air conditioning. Moreover, women, older persons, and persons not in the labor force benefited more from central air conditioning. This last finding is quite plausible because these persons tend to have more exposure to air conditioning at home as they spend more time indoor. Rogot (1992), recognizes the problem of omitted variable bias and attempts to address it by comparing changes in ratio of death rate during hot months versus cold months for persons in households with air conditioning with changes in that ratio for persons in households without air conditioning under the assumption that that ratio would be the same in the absence of air conditioning. This research design solves a series of problems that plagued previous research; however, it fails to account for the fact that the persons who live in households with air condition may differ from those who do not in a way that affects the ratio of death rate during hot versus cold months. For instance, disparities in income and education levels are associated with differences in the occurrence of different illnesses. As a result, it is debatable whether the ratio of death rate in the hot versus cold months is the same across socioeconomic characteristics. Failing to control for such characteristics that are correlated with both cause of death and air conditioning raises questions regarding the ability of this research strategy to identify the causal effect of air conditioning. In addition, to the extent to which air conditioning affects behavior for instance by encouraging sedentary lifestyle it may also affect year-round mortality thus biasing the effect on heat mortality.

There are no studies to our knowledge that investigate the impact of air conditioning on humidity related mortality.

C. Air Conditioning and Migration

Historians have long believed that air conditioning has had a major impact on southern population growth. According to Arsenault (1984), for instance, “In a variety of ways the air conditioner has helped to reverse an almost century-long southern tradition of net out-migration.” Environmental and urban economists have long recognized that local environmental amenities, local real estate markets, and the demographic composition of cities are closely related, and in particular households “vote with their feet” in response to changes in environmental quality (Chay and Greenstone, 2005; Banzhaf and Walsh, 2008).

In addition to the well-documented Reverse Great Migration, which coincides with the South's economic growth and its improved race relations, the spread of air conditioning might also have played an important role in attracting people. Rappaport (2007) provides evidence that population changes during the 1970-2000 period were indeed consistent with the introduction of air conditioning, although the shift in the industrial composition of U.S. employment, increased elderly migration, and the broad-based rise in incomes also played a role.

To our knowledge, no study has been conducted to directly evaluate the impact of air conditioning on migration. Using time-series variation in the cost of air conditioning and cross-regional variation in temperature, we estimate the extent to which the observed migration pattern can be explained by changes in the prevalence of air conditioning.

D. Migration and Mortality

A central proposition in the economics of migration is that migrants tend to be favorably self-selected for labor-market success, because migration is a form of investment (Chiswick, 1999). In the case of health outcomes, however, Black et al. (2011) show that while there was positive selection on the basis of labor market skill in migration during the Great Migration in the early twentieth century, migration of millions of African Americans out of the South to urban areas in the North, Midwest, and West reduced longevity. Black at al. conjecture that the relatively poor health conditions in destination locations (large cities like New York, Detroit, and Chicago) compared with the predominantly rural areas in the South may explain the negative health impact, although their result is also consistent with Deschênes and Moretti's (2009) finding that deaths attributable to cold weather imply significant reduction in longevity and our finding that extreme heat increases mortality in urban areas. Using more recent data, Halliday and Kimmitt (2008) find that, among men younger than age 60, the healthier ones are geographically more mobile. There is no such selection on health in the case of women, conjectured to migrate to follow their spouses.

3. Data and Empirical Strategy

A. Data Sources

Air Conditioning Data. The air-conditioning data come from the Decennial Census of Housing. In 1960, the decennial census included air conditioning for the first time. In particular, item H27 in the questionnaire asks:

Do you have any air conditioning?

- Room unit — 1 only
- Room unit — 2 or more
- Central air conditioning system
- No air conditioning

The air conditioning variable measures the number of units with any type of air conditioning per 10 occupied housing units. Since the air-conditioning question was no longer asked in the 1990 or 2000 decennial censuses, we assemble county-level information about air-conditioning prevalence for years 1960, 1970, and 1980. While the choice of our period is based in part on considerations of data availability, it is defensible in light of the history of residential air conditioning because the 1960-1980 period saw the most significant decline in price and increase in prevalence of air conditioning.

Biddle (2008) provides data on the price of an installed central air system and the price change of room air conditioners over the 1960-1980 period.

Mortality Data. The mortality data are taken from the 1959-2006 Multiple Cause-of-Death (MCOD) Files. The MCOD data provide county-level mortality information by gender-age-race demographic group and by cause of death for all deaths occurring within the United States. While daily mortality data are not available until 1972, monthly data exist for the whole sample period. Our baseline sample consists of monthly mortality data for the years 1960, 1970, and 1980.[4] Since the impact of a given day's temperature may take several days to manifest fully, using monthly mortality data instead of daily data enables us to better capture this full impact.[5] On the other hand, using monthly instead of annual data not only increases the number of observations but also allows us to compare mortality in different seasons over time within the same county and in particular to see if how air conditioning affected heat related mortality versus cold related mortality. We perform our analysis on the sub-sample of white population to reduce concerns of confounds such as the effects of the civil rights movement.

Finally, since we are interested in the impact of residential air conditioning on the mortality in extreme weather, in our baseline sample, we drop all the observations in which the county of occurrence of death is different from the county of residence so as to reduce the noise introduced by deaths during travelling away from home.[6]

Weather Data. The weather data are drawn from the National Climatic Data Center (NCDC) Global Summary of the Day (GSOD), which provide information on the daily mean temperature as well as the mean dew point, mean station pressure, and the total daily precipitation. We follow Barreca (2011) and calculate the mean specific humidity using a standard meteorological formula and information on mean dew point and mean station pressure.

[4] To translate death counts by age from the MCOD data into the corresponding mortality rates, we use population data by gender-age demographic group from the census of population.

[5] According to Deschenes and Moretti (2009) the full impact of a cold day on mortality occurs within 30days.

[6] The fraction of the deaths occurred outside the county of residence is 16.56% in 1960. The figures in 1970 and 1980 are 18.73% and 19.61% respectively. Our results are not sensitive to this restriction – results not reported but available on request.

The Global Summary of the Day (GSOD) files report detailed climatic information by weather station and day. Following Deschênes and Greenstone (2011) we aggregate station-level data at the county level by taking an inverse-distance weighted average of all the measurements from stations that are located within a 200 km radius of each county's centroid.[7]

Other Variables. County-level data on population, age structure, personal income, the fraction of high-school graduates, and the fraction of urban population are taken from the Census of Population.

B. Summary Statistics

Table 1 reports population weighted average monthly mortality rates per 100,000 by gender, age, and cause of death for each of the 3 years used in analysis. There is significant heterogeneity across demographic groups. The most important cause of death is cardiovascular disease, followed by neoplasm (cancers), and respiratory disease.

The summary statistics also report the population weighted number of houses with air conditioning (room or central air conditioning) out of every 10 occupied housing units. The numbers reveal the very rapid spread of air conditioning during the 1960-1980 period.

C. Empirical Strategy

We first consider a simple model relating county-level mortality rates to temperature:

$$(1) \qquad Y_{cmt} = \psi\, AC_{ct} + \sum\nolimits^{J}_{j=1} \theta_j\, TMEAN_{cmtj} + \sum\nolimits^{I}_{i=1} \mu_i\, HMEAN_{cmti} + \delta_J\, TMEAN_{cmtJ} \times AC_{ct} + $$
$$+ \delta_I\, HMEAN_{cmtJ} \times AC_{ct} + \varphi\, PREC_{cmt} + X_{ct}\, \beta + \varepsilon_{cmt},$$

Y_{cmt} is the mortality rate in county c in month m and year t. In our baseline specification, the variables $TMEAN_{cmtj}$ denote the percentage of days in county c, month m and year t for which the daily mean temperature falls in one of five different intervals j, ranging from a mean temperature

[7] We dropped all weather stations at elevations above 7,000 feet because their readings were unlikely to reflect the climacteric conditions experienced by the majority of population within a county. The valid weather measurements are weighted by the inverse of their squared distance to the county centroid.

less than 20°F to a mean exceeding 80°F. The variables $HMEAN_{cmtj}$ denote the percentage of days in county c, month m and year t for which the daily mean humidity falls in one of five different intervals i, ranging from a mean humidity less than 2 grams of water-vapor per kg of air to a mean exceeding 16g/kg. This semi-parametric modeling of weather is adopted to capture the highly nonlinear relationship between temperature and health. The variable $PREC_{cmt}$ measures the total monthly rainfall. X_{ct} is a vector of observable time-varying determinants of fatalities measured at the county level. In our baseline specification, these variables include (log of) personal income, the fraction of high-school graduates, the fraction of urban population, and the age structure of the population.

The stochastic error term ε_{cmt} is equal to $\alpha_{cm} + \gamma_{cm} \times t + \lambda_{st} + u_{cmt}$. The full set of county-by-month fixed effects α_{cm} is included to absorb all unobserved county-month-specific time invariant determinants of the mortality rate. As a result differences in permanent season specific determinants of mortality at county level do not confound our estimates. Average life expectancy in the United States has increased steadily in the past few decades; however, there are large disparities in health improvement across population subgroups defined by geography (Ezzati, et al. 2008). Our equation therefore also includes county specific time trends that are allowed to vary by month, $\gamma_{cm} \times t$. In addition, we also control for time-varying differences in the dependent variable that are common across counties in a state through the state-by-year fixed effects λ_{st} (e.g. state regulations).

The above specification differs from the standard specification in two main ways: (1) the use of the variable AC_{ct} to capture the prevalence of air conditioning, allowing the interaction terms $TMEAN_{cmtJ} \times AC_{ct}$ and $HMEAN_{cmtI} \times AC_{ct}$ to test if air-conditioning prevalence affects the weather-mortality relationship, and (2) we use monthly instead annual data (e.g. Deschênes and

Greenstone, 2011) or daily data (e.g. Deschênes and Moretti, 2009). The main coefficient of interest are the δ.

Our approach uses the sharp variation across counties in changes in air-conditioning prevalence from 1960-1980. Assuming linearity of the effects of air conditioning, we can estimate our “random trend model” by considering the following first-differenced equation:

$$(2) \qquad \Delta Y_{cmt} = \psi\, \Delta AC_{ct} + \textstyle\sum_{j=1}^{J} \theta_j\, \Delta TMEAN_{cmtj} + \sum_{i=1}^{I} \mu_i\, \Delta HMEAN_{cmti} + \Delta(TMEAN_{cmtJ} \times AC_{ct}) + \Delta(HMEAN_{cmtI} \times AC_{ct}) + \varphi\, \Delta PREC_{cmt} + \Delta X_{ct}\beta + \Delta\varepsilon_{cmt},$$

where $\Delta\varepsilon_{cmt} = \gamma_{cm} + \Delta\lambda_{st} + \Delta u_{cmt}$. In other words, fixed county differences in the levels of the dependent variables drop out of the first-differenced model. The full set of $\Delta\lambda_{st}$ is estimated as the state-by-year fixed effects in the first-differenced model.

In the subsequent analysis, equation (2) is estimated for the whole population all together as well as separately for four separate age groups (ages 0-1, 1-44, 45-64, and 65+) so that all parameters are allowed to vary across these age groups. Moreover, we also estimate separate equations for cause-specific mortality rates. The identification assumption of our fixed-effects estimation is that once we control for changes in other observables and the fixed effects, Δu_{cmt} is uncorrelated with changes in air-conditioning prevalence. When the most vulnerable are more likely to have residential air conditioning to protect themselves against heat stress, however, fixed effects estimates may understate the true health benefit of air conditioning.

Our second strategy is to use instrumental-variable method. We use the price of air conditioning apparatus interacted with the annual proportion of hot days and the price of air conditioning apparatus interacted with the annual proportion of high humidity days to instrument for air conditioning prevalence. We instrument the interaction term between air conditioning and monthly hot days with the interaction between the price of air conditioning apparatus and monthly hot days. A similar instrument is used for the interaction term between air conditioning and monthly humid days. The first stage equations for the instrumental variables estimates are:

$$(3)\ \Delta AC_{ct} = \gamma \Delta P_t + \sum_{j=1}^{J} \theta_j\ \Delta TMEAN_{cmtj} + \sum_{i=1}^{I} \mu_i\ \Delta HMEAN_{cmti} + \varphi\ \Delta PREC_{cmt} + \Delta X_{ct}\beta + \Delta\varepsilon_{cmt},$$

$$(4)\ \Delta(TMEAN_{cmtJ} \times AC_{ct}) = \lambda\ \Delta(TMEAN_{cmtJ} \times \Delta P_t) + \sum_{j=1}^{J} \theta_j\ \Delta TMEAN_{cmtj} + \sum_{i=1}^{I} \mu_I\ \Delta HMEAN_{cmti} + \varphi\ \Delta PREC_{cmt} + \Delta X_{ct}\beta + \Delta\varepsilon_{cmt},$$

$$(4)\ \Delta(HMEAN_{cmtI} \times AC_{ct}) = \lambda\ \Delta(HMEAN_{cmtJ} \times \Delta P_t) + \sum_{j=1}^{J} \theta_j\ \Delta TMEAN_{cmtj} + \sum_{i=1}^{I} \mu_I\ \Delta HMEAN_{cmti} + \varphi\ \Delta PREC_{cmt} + \Delta X_{ct}\beta + \Delta\varepsilon_{cmt},$$

The unit of observation (county-month) is more detailed than the level of variation of the independent variable of interest (air conditioning prevalence), the county level. It is likely that the error terms are correlated within county over time. Consequently, this paper reports standard errors clustered at the county level, a method that allows for an arbitrary autocorrelation process (Bertrand et al., 2004). Second the estimates of mortality rates from large population counties are more precise. To correct for heteroskedasticity associated with these differences in precision we fit weighted versions of our equations, where the weight is the sample population in the county.

For the purpose of investigating the impact of changes in AC prevalence on migration we estimate the following equation:

$$(5)\ \text{Net Migration}_{cmt} = \psi\ \Delta AC_{ct} + \sum_{j=1}^{J} \theta_j\ TMEAN_{cmtj} + \sum_{i=1}^{I} \mu_i\ HMEAN_{cmti} + \varphi\ PREC_{cmt} + + X_{ct-1}\beta + \varepsilon_{cmt},$$

In this specification Y_{cmt} is the net decennial migration in county *c* in month *m* taking place during decade *t*. It could be either the migration between 1960 and 1970 or the migration between 1970 and 1980. ΔAC_{ct} is the change in air conditioning prevalence over the same periods. In this specification, the variables $TMEAN_{cmtj}$ denote the average percentage of days in county *c*, month *m* during decade *t* for which the daily mean temperature falls in one of five different intervals *j*. The *j* intervals are the same ones considered before. The variables

$HMEAN_{cmti}$ measure humidity and bear a similar interpretation as the $TMEAN_{cmti}$ variables. X_{ct-1} is a vector of observable time-varying demographic variables measured at the county level at the beginning of the decade investigates. These variables are (log of) personal income, the fraction of high-school graduates, the fraction of urban population, and the age structure of the population.

Instrumental-variable estimates using the price of air conditioning apparatus interacted with the annual proportion of hot days and the price of air conditioning apparatus interacted with the annual proportion of days with high humidity to instrument for air conditioning prevalence are also reported. The migration regressions are weighted by county population and report standard errors clustered at county level.

4. Results

We begin by estimating (2) using data for all white population. Rogot et al. (1992) find that the health benefit of air conditioning is higher for women than for men, explained by the fact that women spend more time at home. We follow his lead and also report results separately by gender. The coefficient on each temperature bin is normalized with the 60°-80°F category so that the reported effects are all relative to the mortality rate associated with a day where the temperature is between 60°-80°F (lowest mortality rate temperature bin in our sample). The coefficient on each humidity bin is normalized with the 8-12 g/kg specific humidity category.

To compare our results with previous findings, we also present results using the standard pooled OLS regressions. The first column of table 2 reports the pooled OLS regressions and shows that on average, air conditioning prevalence is indeed negatively correlated mortality. The air conditioning-high temperature interaction term suggests that air conditioning has no significantly different impact on mortality in extreme hot weather (i.e. average temperature above 80°F; note that a daily average of 80°F implies daily maxima of over 90°F[8]). The fact that air conditioning has an effect on health but that effect is independent of ambient temperature suggests that omitted variables, such as trends in mortality determinants, may be a problem.[9]

Once fixed effects are included, the coefficient on air conditioning becomes insignificant and the interaction term with temperature becomes marginally significant for women. When we instrument for air conditioning both the direct effect and the interaction term become larger but only the interaction term is statistically significant, suggesting that air conditioning significantly reduces mortality when (and likely only when) temperature is extremely high. Moreover, the main effect of high temperature becomes significant, indicating that in the absence of air conditioning, high temperature increases mortality. These results are consistent with selection by health where selection effects are stronger for males. In particular frail individuals, especially males, are more likely to have air conditioning. Thus our results uphold previous literature indicating location choices are consistent with selection on health for males but less so for females (Halliday and Kimmitt, 2008).

Our estimates indicate that in a typical month (with 6.7% of days with temperatures over 80°F) having an additional 10% of occupied houses equipped with air conditioning is associated with approximately 0.4 fewer monthly deaths per 100,000. During the 1960-1980 period the air conditioning prevalence in the county of the average person increased from 10% to 50% translating in ~37,000 fewer annual deaths calculated using an average population over the period of 200 million. Figure 1 shows estimated mortality function of monthly incidence of

[8] Metzger et al (2010) find that mortality in New-York City increases sharply when the heat index reached 95F. However their analysis was performed using 1997-2006 data and evaluates the mortality response to heat when people use adaptation technology.

[9] Note that the variables in the interaction term are not demeaned such that the mean effect of the air conditioning variable is calculated for the case of a month with not hot days.

extreme temperatures (daily averages over 80°F) under different scenarios of air conditioning prevalence.

We find no evidence of an economically significant differential impact using the female sample than using the male sample. An additional 10% of occupied houses equipped with air conditioning is associated with 0.36 fewer monthly deaths per 100,000 women and 0.43 fewer monthly deaths per 100,000 men.

Other coefficients seem to be plausibly estimated. For example, cold weather (i.e. average temperature below 40°F) significantly increases mortality. Total precipitation does not seem to affect heath. Note that once controlling for fixed effects, socioeconomics variables do not appear to be significantly correlated with mortality (not reported due to space constraints but available on request). This suggests that selection on unobservables may not be a major concern when exploiting within-county weather fluctuation over time.

Because mortality is significantly affected by the degree of urbanization and the age structure of the population, we re-estimate our model using different subsamples based on rurality and age.

4.1. Estimated Effect of Air Conditioning by Age

Table 3 summarizes the results by age group. As expected the older age group appears to suffer more from extreme heat, and the aged are also more likely to benefit from air conditioning. In fact we find no significant effect on any other age group than people above 65. While previous literature found some evidence of an effect of high temperature on birth outcomes, we find no indication of a significant effect on infant mortality ages 0-1 year old. It is possible that air conditioning affects birth outcomes through its effect on the incidence of stillbirth but our data does not allow us to test this hypothesis so we leave this question for future research.

4.2. Estimated Effect of Air Conditioning by Cause of Death

In table 4, we consider five mortality causes: cardiovascular diseases, neoplasms, respiratory disease, infectious diseases, and motor vehicle accidents. Deschênes and Moretti (2009) show that cardiovascular disease, the single most important cause of death in the population as a whole, exhibits strong seasonality, and that excess mortality immediately following exposure to high temperatures is mostly attributable to cardiovascular diseases. They also show that respiratory disease mortality is concentrated in the winter months, whereas cold temperature reduces mortality due to motor vehicle accident among the male population. Finally, there is no significant seasonality in mortality due to neoplasms, the second major cause of mortality. We also consider infectious diseases because by improving intra-household environment air conditioning is expected to encourage people to spend more time inside, thus, reducing exposure to infectious diseases.

In table 4 we present results organized by mortality cause using the subsample of white male and female, respectively. We find significant heterogeneity in our results. Among the female population, extreme hot weather significant increases mortality due to cardiovascular diseases and respiratory diseases, and air conditioning significantly reduces this adverse health impact. There is some evidence of a reduction in mortality from infectious diseases but it is not significant at conventional significance levels. Among all causes of death, we find the largest impact is in the case of cardiovascular diseases. Note that all these three causes of death exhibit seasonality.

In general, the effects in the male sample are smaller and less precisely estimated. We find only weak evidence of an effect on cardiovascular disease and the only effect significant at conventional significance levels is the effect on neoplasm mortality, not known to exhibit seasonality. Nevertheless the significant effect of heat on neoplasm mortality is not a new result. Huynen et al (2001) and Deschenes and Moretti (2009) also found evidence of an immediate effect of heat on neoplasm. We add to those results the finding that air conditioning is associated with a decrease in neoplasm mortality among males, possibly an indication of decreased exposure to elements that would otherwise further weaken a frail body. Interestingly on the sample of males we also find that air conditioning reduces humidity related mortality from respiratory disease.

4.3. Estimated Effect of Air Conditioning by Urban-Rural Residence

Columns 1 and 3 of table 5 shows that while extreme heat increases mortality in urban counties, air conditioning significantly reduces it. This relationship does not hold in rural counties in the case of women.[10] We still find a significant effect of air conditioning on male mortality but it is smaller than the effect obtained on the urban sample. The results presented here suggest that the temperature-air conditioning-mortality relationship is mostly an urban phenomenon. The urban heat island effect — that urban areas typically have higher heat indexes than surrounding suburban or rural areas because of heat absorbed by buildings and roadways — has been well documented (e.g. Basu, and Samet, 2002). We add to the literature that the health benefit of air conditioning is also an urban phenomenon.

[10] This result is not driven by noise. If we restrict our sample of rural counties to counties with a population exceeding 10,000 we find very similar results. The IV estimate of the interaction between air conditioning and temperatures over 80F on the female sample is -0.018 with standard errors of 0.020 and on the male sample is -0.031 with standard errors 0.022, thus not statistically significant in either case.

4.4. Estimated Effect of Air Conditioning on Migration

We find some evidence of general equilibrium effects. The development of air conditioning has made the South and the Sunbelt in general more attractive places to live and work. Improved consumer amenities in hot areas may increase geographical mobility and thus reduce migrants' exposure to cold days, and thus cold related mortality. The model presented in equation (5) was estimated and the results were reported in table 6. We find a positive association between changes in air conditioning prevalence and migration. Note that the OLS results could mean that once the technology became available people chose to migrate toward South because now they can protect themselves against heat through air conditioning, and thus this migration led to the increase in air conditioning prevalence. Else it could be people migrate toward areas with high air conditioning prevalence because in these areas the cost of installing the technology is cheaper perhaps because of specific characteristics of housing supply.

When we instrument changes in air conditioning prevalence with interaction term between changes in price and percentage annual hot days (average over 80F) and the interaction between changes in price and percentage annual days with high humidity (specific humidity over 16g/kg) we find very similar results, an indication the causality runs from easy access to this technology to migration and not the other way around. Without specific data regarding the precise point of origin of the migrants it is difficult to estimate the impact of air conditioning on health mediated through migration.

6. Conclusions

To summarize, using sharp variation in air conditioning prevalence due to technological progress we find evidence that an additional 10% of occupied houses equipped with air conditioning is associated with approximately 5 fewer deaths per 100,000. Most of the effect is driven by a reduction in urban mortality with a smaller effect on men and no effect on women in rural areas. In general elderly derive higher benefits from air conditioning. In addition, our results indicate that air conditioning leads to an increase in migration.

In 1960 the average person lived in a county where approximately 10% of occupied houses were equipped with air conditioning. By 1980, the end of our sample, the average person lived in a county where approximately 50% of occupied houses were equipped with air conditioning. In the South the number is as high as 70%. Our estimates imply that this rapid increase in air conditioning prevalence from 10% to 50% amounted to approximately 37,000 lives saved each year. These results indicate that air conditioning was able to provide effective protection against the impact of high temperature and to provide strong enough incentives to alter location decisions within a decade. These results are consistent with the predicted effects of climate change – as temperature and possibly humidity increase in some areas people that cannot protect themselves against extreme climates will migrate.

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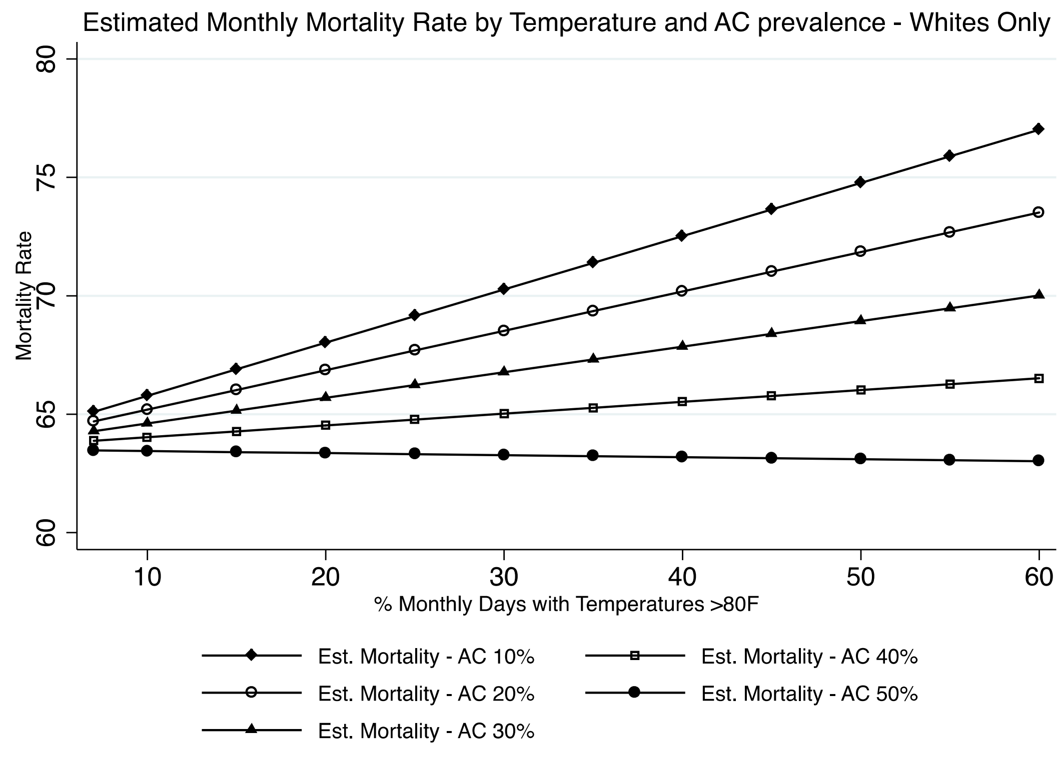
Figure 1



Estimated Monthly Mortality Rate by Temperature and AC prevalence - Whites Only
Mortality Rate
80
75
70
65
60
10
20
30
40
50
60
% Monthly Days with Temperatures >80F
Est. Mortality - AC 10%
Est. Mortality - AC 20%
Est. Mortality - AC 30%
Est. Mortality - AC 40%
Est. Mortality - AC 50%

Table 1. Summary Statistics

		1960	1970	1980
AC		1.214	3.580	5.517
Mortality Rate - All		67.768	64.891	60.378
Mortality Rate by Gender	- Females	57.98	56.434	55.528
	- Males	77.927	73.884	65.522
Mortality Rate by Age	- < 1	166.174	114.91	58.011
	- 1 to 44	7.531	7.073	6.299
	- 45 to 64	76.244	71.778	58.092
	- > 65	441.35	416.73	367.777
Mortality Rate	- Cardiovascular	30.861	36.637	31.950
	- Neoplasm	11.041	11.374	12.576
	- Respiratory	3.403	3.659	4.054
	- Infectious	0.617	0.427	0.418
	- Motor Vehicle	1.096	1.324	1.261
Percent of Days >80°F		4.757	5.480	9.314
Percent of Days 60-80°F		40.556	39.999	36.980
Percent of Days 40-60°F		28.818	31.055	31.548
Percent of Days 20-40°F		21.423	18.733	18.217
Percent of Days <20°F		4.446	4.732	3.940
Percent of Days >16g/kg humidity		3.046	3.522	0.698
Percent of Days 12-16g/kg humidity		12.886	12.602	2.720
Percent of Days 8-12g/kg humidity		22.736	21.123	6.240
Percent of Days 4-8g/kg humidity		29.892	30.210	19.509
Percent of Days <4g/kg humidity		31.440	32.543	70.832
Monthly Total Precipitation		5,670,255	5,416,137	352,690.1
Age 0-1		2.217	1.747	1.513
Age 1-44		67.846	67.085	66.533
Age 45-64		20.337	21.029	20.204
Age >65		9.600	10.140	11.750
Log (income)		7.607	7.869	8.104
High-school		41.641	53.277	67.146
Urban		68.465	71.649	71.686

All entries are weighted averages where the weight is county population. The data is for white population only. Mortality rates are expressed as deaths per 100,000 population. AC variable measures the number of units with any type of air conditioning per 10 occupied housing units.

Table 2: The Effect of Air Conditioning on Monthly All-Cause Mortality Rates

	All			Female		Male	
	Pooled OLS	FE OLS	FE IV	FE OLS	FE IV	FE OLS	FE IV
	[1]	[2]	[3]	[4]	[5]	[6]	[7]
AC	-2.087**	0.122	-2.991	0.035	-0.596	0.166	-5.854
	(0.837)	(0.928)	(4.169)	(0.781)	(3.216)	(1.082)	(5.737)
AC×%Days >80°F	-0.038	-0.014	-0.058**	-0.016*	-0.054**	-0.014	-0.065**
	(0.038)	(0.009)	(0.027)	(0.009)	(0.024)	(0.012)	(0.033)
AC×%Days >16g/kg	0.014	-0.002	0.007	-0.003	0.004	-0.001	0.012
	(0.011)	(0.005)	(0.007)	(0.005)	(0.007)	(0.007)	(0.009)
% Days >80°F	0.327	0.069	0.283**	0.079	0.272**	0.063	0.302**
	(0.324)	(0.044)	(0.117)	(0.048)	(0.109)	(0.058)	(0.142)
% Days 40-60°F	0.109**	0.023	0.026	0.003	0.004	0.044	0.050**
	(0.054)	(0.029)	(0.019)	(0.028)	(0.019)	(0.035)	(0.023)
% Days 20-40°F	0.189*	0.100***	0.105***	0.069**	0.070***	0.132***	0.142***
	(0.101)	(0.034)	(0.022)	(0.033)	(0.022)	(0.041)	(0.027)
% Days <20°F	0.180***	0.255***	0.261***	0.216***	0.217***	0.295***	0.307***
	(0.020)	(0.033)	(0.025)	(0.035)	(0.026)	(0.040)	(0.031)
% Days >16g/kg	-0.203	0.021	-0.050	0.032	-0.017	0.011	-0.091
	(0.131)	(0.041)	(0.052)	(0.045)	(0.053)	(0.055)	(0.069)
% Days 12-16g/kg	-0.055	-0.013	-0.024	-0.006	-0.012	-0.020	-0.037
	(0.036)	(0.025)	(0.026)	(0.024)	(0.022)	(0.031)	(0.033)
% Days 4-8g/kg	-0.097	-0.026**	-0.024***	-0.028**	-0.028***	-0.023	-0.021
	(0.074)	(0.012)	(0.009)	(0.013)	(0.009)	(0.016)	(0.014)
% Days <4g/kg	-0.142	-0.039**	-0.042***	-0.044***	-0.044***	-0.035	-0.040***
	(0.112)	(0.017)	(0.011)	(0.015)	(0.010)	(0.022)	(0.016)
Monthly Precipitations	0.321*	0.0164	-0.036	0.033	0.026	0.003	-0.101
	(0.172)	(0.056)	(0.110)	(0.056)	(0.089)	(0.064)	(0.141)
First Stage F							
- AC eq			14.21		13.59		14.30
- AC x >80°F eq			100.49		102.41		98.49
- AC x >16g/kg eq			60.92		59.65		62.13
Obs	109332	72888	72888	72888	72888	72888	72888

All regressions are run on a balanced panel of 3037 counties, and they are weighted by county population. All data is for white population only. Columns [1] reports results from pooled OLS estimation using the level equation (1) in the text. Results from the fixed effects estimation, reported in columns [2]-[7], are estimated using stacked 1960-1970 and 1970-1980 changes as described in the first-differenced equation (2) in the text. All regressions control for total monthly precipitation, age structure of the population, log income, education, and percent urban. Specifications [2]-[4] include county-by-month and state-by-year fixed effects. We use the price of air conditioning apparatus interacted with the annual proportion of hot days and with the annual proportion of high humidity days to instrument for air conditioning prevalence. We instrument the interaction AC×%Days >80°F with the interaction between the price of air conditioning apparatus and monthly hot days. A similar instrument is used for the interaction AC×%Days >16g/kg. Robust standard errors clustered at county level are reported in parentheses. * significant at 10%; ** significant at 5%; *** significant at 1%.

Table 3: Estimates of the Effect of Air Conditioning on Monthly All-Cause Mortality Rates, By Age

	Age 0-1		Age 1-44		Age 45-64		Age 65	
	OLS	IV	OLS	IV	OLS	IV	OLS	IV
AC	-3.042	-0.437	-0.119	-1.527*	-0.561	-9.613	1.400	6.307
	(2.715)	(21.78)	(0.123)	(0.873)	(1.045)	(7.540)	(5.560)	(18.95)
AC×% Days >80°F	0.017	0.010	-0.002	-0.007	-0.008	-0.036	-0.114**	-0.360***
	(0.056)	(0.094)	(0.003)	(0.005)	(0.016)	(0.039)	(0.056)	(0.104)
AC×% Days >16g/kg	0.034	-0.021	-0.001	0.002	-0.006	0.002	0.021	0.056
	(0.044)	(0.046)	(0.002)	(0.002)	(0.009)	(0.013)	(0.032)	(0.035)

All data is for white population only. All regressions are weighted by county population in the relevant age group. All results are estimated using stacked 1960-1970 and 1970-1980 changes as described in the first-differenced equation (2) in the text. All regressions control for the entire distribution of temperatures and humidity, total monthly precipitation, log income, education, and percent urban. All regressions include county-by-month and state-by-year fixed effects. We use the price of air conditioning apparatus interacted with the annual proportion of hot days and with the annual proportion of high humidity days to instrument for air conditioning prevalence. We instrument the interaction AC×%Days >80°F with the interaction between the price of air conditioning apparatus and monthly hot days. A similar instrument is used for the interaction AC×%Days >16g/kg. Robust standard errors clustered at county level are reported in parentheses.
* significant at 10%; ** significant at 5%; *** significant at 1%.

Table 4: IV Estimates of the Effect of Air Conditioning on Monthly All-Cause Mortality Rates, By Gender and Cause of Death

	Cardiovascular Disease		Respiratory Disease		Infectious Diasease		Neoplasm		Traffic Accidents	
	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male
AC	-0.550	-4.150	0.321	-0.307	-0.071	-0.170**	-0.502	0.401	-0.0410	0.207
	(2.329)	(3.625)	(0.336)	(0.645)	(0.068)	(0.083)	(0.796)	(0.971)	(0.214)	(0.368)
AC×% Days >80°F	-0.044***	-0.037*	-0.009***	-0.006	-0.0009*	0.0000	0.002	-0.011**	-0.0005	0.0006
	(0.016)	(0.019)	(0.002)	(0.005)	(0.0005)	(0.0004)	(0.004)	(0.005)	(0.0012)	(0.0020)
AC×% Days >16g/kg	0.007	0.006	0.001	-0.0038**	-0.0001	0.0001	-0.002	0.003	-0.0007	-0.0001
	(0.005)	(0.006)	(0.001)	(0.0017)	(0.0003)	(0.0002)	(0.002)	(0.002)	(0.0007)	(0.0011)

All data is for white population only. All regressions are weighted by county population. All results are estimated using stacked 1960-1970 and 1970-1980 changes as described in the first-differenced equation (2) in the text. All regressions control for the entire distribution of temperatures and humidity, total monthly precipitation, age structure of the population, log income, education, and percent urban. All regressions include county-by-month and state-by-year fixed effects. We use the price of air conditioning apparatus interacted with the annual proportion of hot days and with the annual proportion of high humidity days to instrument for air conditioning prevalence. We instrument the interaction AC×%Days >80°F with the interaction between the price of air conditioning apparatus and monthly hot days. A similar instrument is used for the interaction AC×%Days >16g/kg. Robust standard errors clustered at county level are reported in parentheses.

* significant at 10%; ** significant at 5%; *** significant at 1%

Table 5. IV Estimates of the Effect of Air Conditioning on Monthly All-Cause Mortality Rates, By Gender and Urban

	Female		Male	
	Urban	Rural	Urban	Rural
AC	0.099	4.043	-9.030	-2.215
	(5.306)	(5.784)	(10.11)	(7.653)
AC×% Days >80°F	-0.070**	-0.017	-0.069*	-0.043**
	(0.031)	(0.018)	(0.040)	(0.021)
AC×% Days >16g/kg	0.011	-0.007	0.017	-0.008
	(0.010)	(0.013)	(0.012)	(0.015)
First Stage F - AC eq.	4.43	16.83	4.82	16.79
- AC x >80°F eq.	45.33	442.09	43.70	440.08
- AC x >16g/kg eq.	54.66	167.81	56.91	164.63
Observations	17,352	47,664	17,352	47,664

Urban (rural) counties are defined as counties that had more (less) than 50 percent urban population in all years. There are 723 urban counties and 1986 rural counties. All data is for white population only. All regressions are weighted by county population. All results are estimated using stacked 1960-1970 and 1970-1980 changes as described in the first-differenced equation (2) in the text. All regressions control for the entire distribution of temperatures and humidity, total monthly precipitation, age structure of the population, log income, education, and percent urban. All regressions include county-by-month and state-by-year fixed effects. We use the price of air conditioning apparatus interacted with the annual proportion of hot days and with the annual proportion of high humidity days to instrument for air conditioning prevalence. We instrument the interaction AC×%Days >80°F with the interaction between the price of air conditioning apparatus and monthly hot days. A similar instrument is used for the interaction AC×%Days >16g/kg. Robust standard errors clustered at county level are reported in parentheses.
* significant at 10%; ** significant at 5%; *** significant at 1%.

Table 6. The Effect of Air Conditioning on Migration

	All		Female		Male	
	OLS	IV	OLS	IV	OLS	IV
AC	4.786***	4.811**	4.810***	4.365**	4.888***	5.166**
	(0.770)	(1.994)	(0.783)	(2.040)	(0.771)	(2.077)
% Days >80°F	1.149	1.152*	1.242	1.182*	1.166	1.203*
	(0.769)	(0.682)	(0.786)	(0.705)	(0.775)	(0.683)
% Days 40-60°F	1.600**	1.601***	1.579**	1.547***	1.598**	1.618***
	(0.698)	(0.498)	(0.739)	(0.516)	(0.737)	(0.526)
% Days 20-40°F	2.072**	2.073***	2.031*	2.017***	2.050**	2.060***
	(0.996)	(0.709)	(1.050)	(0.739)	(1.020)	(0.731)
% Days <20°F	1.048	1.054	1.169	1.070	0.894	0.958
	(0.877)	(0.784)	(0.896)	(0.793)	(0.910)	(0.826)
% Days >16g/kg	-1.161**	-1.161***	-1.123**	-1.120***	-1.201**	-1.203***
	(0.549)	(0.385)	(0.572)	(0.406)	(0.541)	(0.377)
% Days 12-16g/kg	-0.994*	-0.993***	-1.068**	-1.076***	-0.932*	-0.927***
	(0.521)	(0.356)	(0.542)	(0.371)	(0.516)	(0.353)
% Days 4-8g/kg	-1.190**	-1.191***	-1.211**	-1.202***	-1.180**	-1.185***
	(0.486)	(0.356)	(0.512)	(0.373)	(0.477)	(0.352)
% Days <4g/kg	-0.920***	-0.920***	-0.931***	-0.929***	-0.917***	-0.918***
	(0.332)	(0.235)	(0.348)	(0.246)	(0.328)	(0.232)

All data is for white population only. All regressions are weighted by county population. All regressions control for total monthly precipitation, lag age structure of the population, lag log income, lag education, and lag percent urban. The dependent variable is decennial net migration for two decades: 1960-1970 and 1970-1980. All regressions include county and state-by-year fixed effects. The instruments are price of air conditioning apparatus interacted with the annual proportion of hot days and the price of air conditioning apparatus interacted with the annual proportion of days with high humidity. Robust standard errors clustered at county level are reported in parentheses.
* significant at 10%; ** significant at 5%; *** significant at 1%.