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Associations Between Climate, Latitude, Fertility and the Decline of the US Sex Ratio at Birth

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I am submitting herewith a dissertation written by Michael C. Meyers entitled "Associations Between Climate, Latitude, Fertility and the Decline of the US Sex Ratio at Birth." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geography.

Bruce A. Ralston, Major Professor

We have read this dissertation and recommend its acceptance:

Shih-Lung Shaw, Micheline van Riemsdijk, Agricola Odoi

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Associations Between Climate, Latitude, Fertility and the Decline of the US Sex Ratio at Birth

A Dissertation Presented for
the Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Michael C. Meyers
May 2012

Dedication

To my beloved Laura

and

Timothy, Joshua, and Nicholas
Brian, Andy, Steven, and Charles,
the seven men who are our children

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Abstract

The US sex ratio at birth (SRB) has declined since 1970, while ambient temperatures have been increasing. This study examines the temporal and spatial variation of the US SRB from 1979–2002 in association with fertility rates and climate variables. Approximately 62.8 million birth records from the National Center for Health Statistics were linked to monthly climate division data and county level socioeconomic variables to evaluate the association of SRB and environmental conditions at or near the time of conception.

Seasonal variation in US SRB is detectable in time series analysis, and is somewhat in phase with variation in fertility. Logistic regression analysis shows that temperature in the month before conception is significantly positively correlated with the likelihood of a male birth when birth order, maternal age, maternal education, plurality, gestation length, race, and Hispanic origin are controlled. This association was significant in models that include all births from 1979–1988, non-Hispanic white births from 1979–1988, and all births in US large counties from 1979–2002. Geographic nonstationarity of US SRB was found in smoothed rate climate division maps for 1979–1988, with higher SRB in latitudes below 40 degrees N, especially in the southeastern US. However, both the overall rates of summer conception and the likelihood of summer male conception are reduced in lower latitudes relative to higher ones.

A logistic regression model was also fit using only non-Hispanic births from US large counties from 1989–2002. In addition to a significant positive association of sex ratio and temperature in the month before conception, deviation from normal monthly temperature during the month of conception, compared to the 1971–2000 baseline temperature, is significantly associated with sex ratio variation. In this population, fewer males were conceived when temperature extremes were significantly above normal; more males were conceived when temperatures were significantly below normal. In both high and low latitude zones over this period, the peak of male conceptions shifted to earlier in the year. Variation in SRB is potentially a sentinel health event and this research suggests that the association between temperature and SRB should be integral to any study of SRB variation across large geographic areas or long time periods.

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Chapter 1: Introduction

Statement of the Problem: The Decline of the US Sex Ratio at Birth

The human sex ratio at birth (SRB)[1] has been of scientific interest for at least four centuries. This interest arises from the fundamental biological question of sex (why two genders?) and from attempts to monitor SRB in association with virtually any question of variation in human populations. For humans as well as other species, SRB can vary according to changes in the environment. Because SRB is a quasi-constant biologic variable, deviation from typical patterns of SRB piques concern and curiosity among researchers. The recent decline in human sex ratio at birth in the US and elsewhere has launched a number of studies to explain this phenomenon in terms of the many social, cultural and biological factors that are hypothesized to influence SRB. Identifying why the SRB decline in the US has occurred would not only increase basic knowledge of human biology, but could also provide an early warning of broad scale changes in human health and the environment.

Part of the appeal of the SRB statistic is its availability. The first scientific paper using inferential statistics found that male births were predominant (51.6 percent) in the records of London's Anglican churches (Graunt 1662). Today, the male proportion of births within each nation globally averages about 51.3 percent, but consistent regional variations have been found (Navara 2009). Currently high SRBs in China and India are at least partially attributed to sex-selective abortion and greater preference for sons, but sex-selective practices are not believed to be a significant factor in the SRB in most locations. The reasons for the low SRB in many countries of the African continent are not known, and some researchers dispute these values because birth records are incomplete in many of these and other nations of lower economic status. Even in the US, accurate national recording of births is a relatively recent practice.

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[1] The proportion of males to females born is termed variously sex ratio at birth, natal sex ratio, the offspring sex ratio, male proportion of births, or the secondary sex ratio. I will use the term "sex ratio at birth" here, but the values I report are technically the male proportion and not the ratio of males to females. High SRBs refer to those in which male births are higher than the norm; low SRBs, those with lower than normal male births. Thus, a decline in SRB refers to a lower than normal male proportion of births.

Poor birth registration records and cultural practices such as sex selective abortion in certain regions make the study of biological reasons for human SRB variation difficult. Current theories of sex ratio allocation hypothesize natural selection as a determinant of SRB variation because parents in certain populations may have greater success in producing offspring who mate and give them grandchildren if these parents favor one sex over another (Fisher 1930, 1958). Research has supported the theory that individuals in at least some species can adjust the sex ratio of their offspring in response to environmental conditions (Trivers and Willard 1973), although the physiological mechanisms underlying this response are not well understood. In the last 10 years, the decline in the male proportion of births in many developed nations has raised the concern that these populations may be responding to environmental or other social or cultural challenges (Davis et al. 1998).

For the last decade, the US SRB has been at its lowest rate since national records have been reliably recorded (Figure 1). The Centers for Disease Control/National Center for Health Statistics (NCHS) researchers examined the US sex ratio since 1940 and concluded from a joinpoint regression that significant changes in the directional trend of SRB had occurred in the late 1950s, when male births began to increase compared to earlier years; in 1970 a significant trend of decreasing male births began (Mathews and Hamilton 2005; Figure 2).

Identifying the reason for the decline is complicated by the large number of factors that have been shown to influence the sex ratio at birth. Many of these are individual characteristics of the parents or child, including age, race, and Hispanic origin of the mother and the birth order of the child (Mathews and Hamilton 2005); the reasons for these associations are not fully understood. Hypothesized influences may begin at or before conception, according to theories that the parental hormonal environment at or near conception time partially controls the sex of offspring (James 1996a). SRB may also be influenced by a mechanism that causes early abortion of males. Individual diet and health practices may determine the success of a pregnancy differently for a boy or girl, given the prevailing theory that males require more

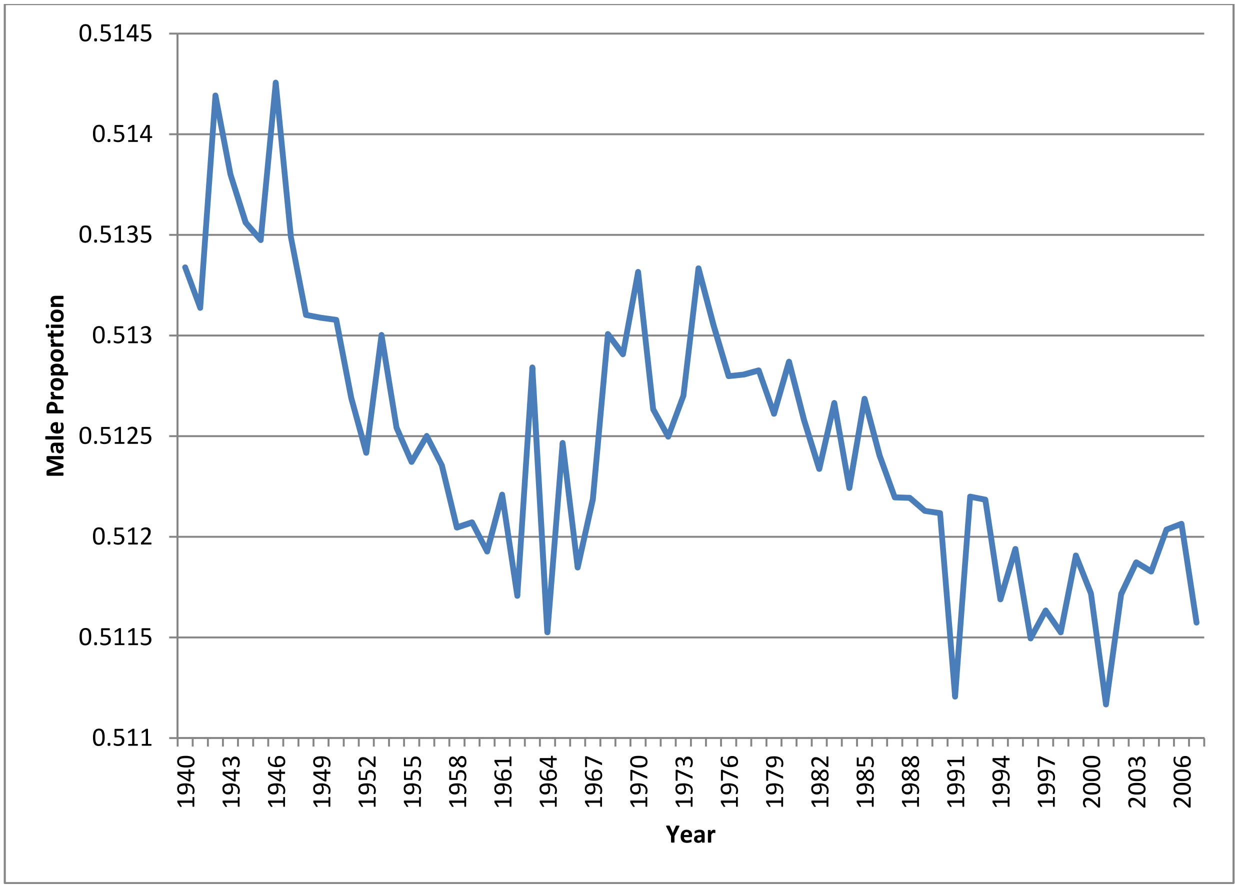
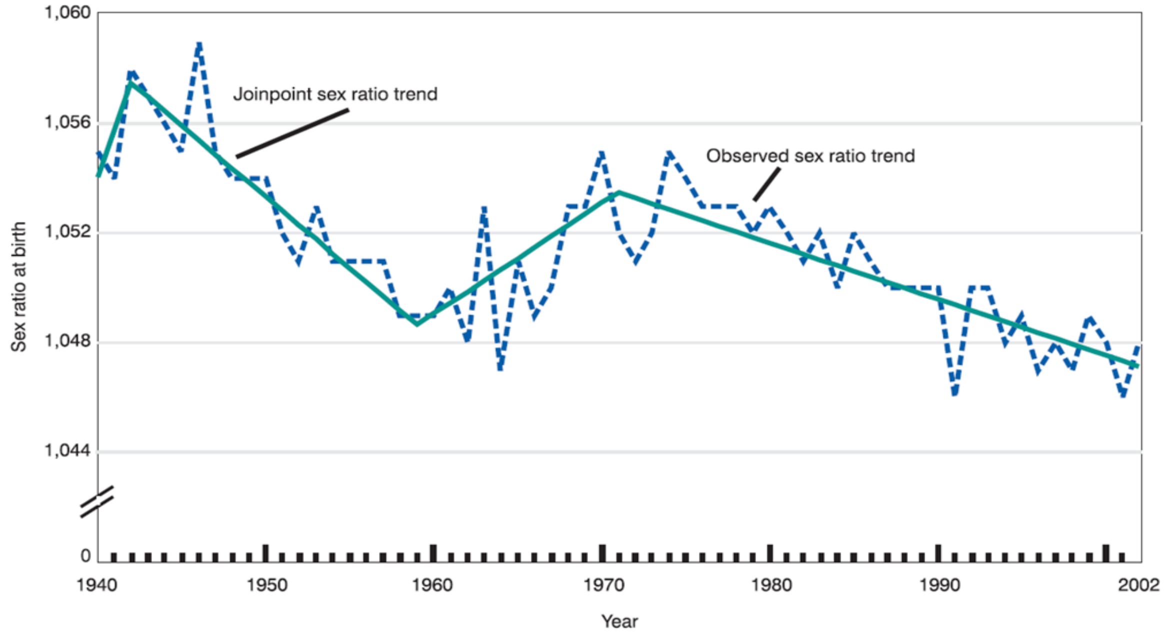


Figure 1. US sex ratio at birth, 1940–2007 (Mathews and Hamilton 2005 and Martin et al. 2005, 2006, 2007, 2008, 2009, 2010).



NOTES: Sex ratio at birth is the number of male births divided by the number of female births multiplied by 1,000. For an explanation of joinpoint see "Technical Notes" and reference 7.

Figure 2. US Sex ratio at birth and joinpoint segments 1940–2002 (Reproduced from Mathews and Hamilton 2005).

resources and are more vulnerable to wasting in a low quality prenatal environment (Ingemarsson 2003, Catalano 2008).

Some recent studies of the US SRB decline hypothesize that it is a result of demographic and cultural changes occurring since 1970. These factors may have directly or indirectly affected the mother's hormonal environment at conception, resulting in fertility or health care trends that adversely affect gestation of the more vulnerable male fetus. Demographic and health researchers are considering the variation in SRB as a result of delayed fertility of educated women while careers are being established, changes in the western diet, the increased use of fertility drugs for conception, particularly among older women, changes in multiple birth rates (plurality), increase in the number of unmarried mothers, an increase in maternal eating disorders, a decreased rate of teenage pregnancy, and better rates of survival due to improved prenatal care. In general, the children of mothers classified by the NCHS as Asian/Pacific Islander or white have higher sex ratios than the national average, while Hispanic, black, and

Native American mothers produce fewer boys (Mathews and Hamilton 2005). Increases in the relative proportion of total births to Hispanic mothers have been considered as a factor in the US sex ratio decline (e.g., Branum et al. 2009). However, no single demographic trend has been shown to account for the decline in SRB among the general population in the US, nor why this decline has not been observed among both white and black births.

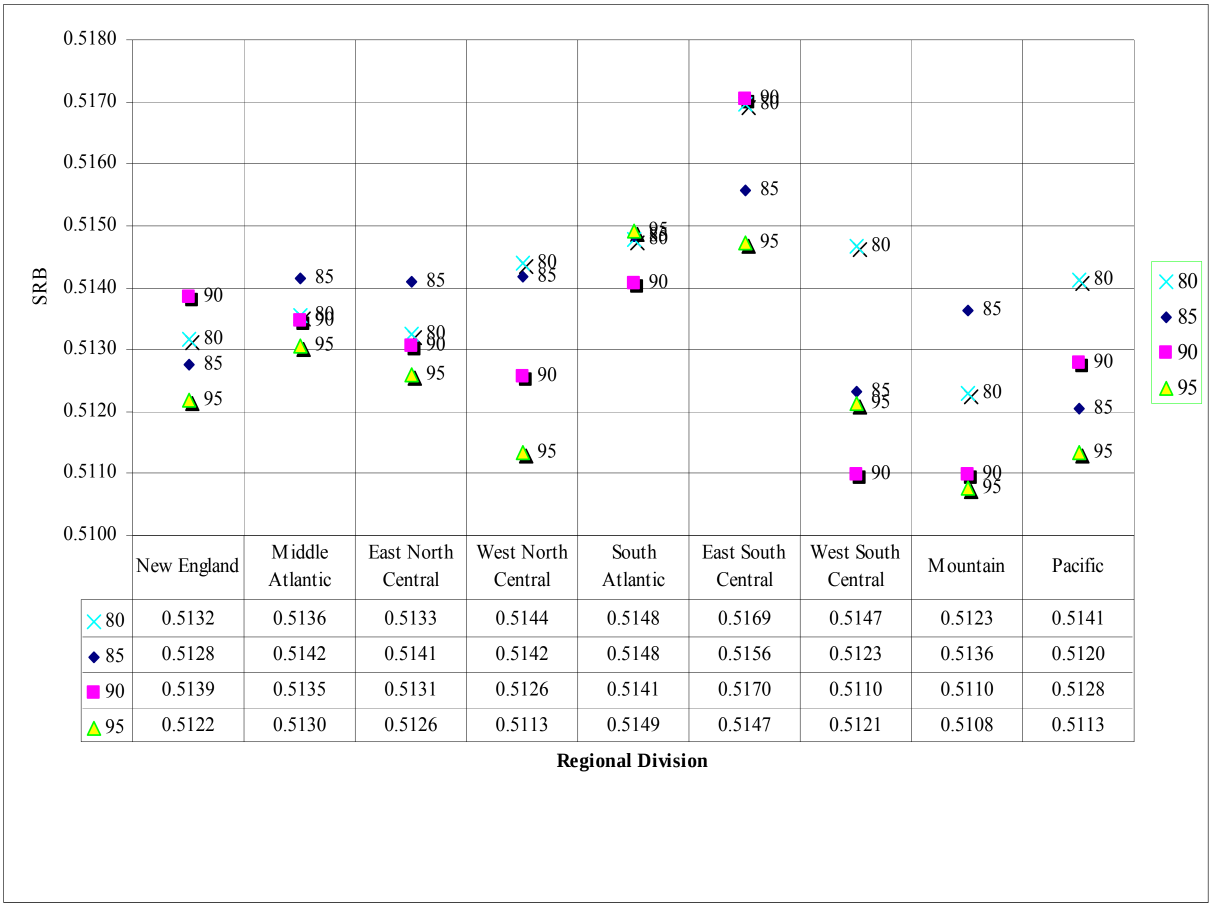
External stressors such as economic depression (Catalano 2003), earthquakes (Fukuda et al. 1998), or war (Zorn et al. 2002) have also been found in association with lower SRB. The SRB decline in the US and some other developed nations has been also attributed by some investigators to widespread exposure to environmental endocrine disrupting chemicals. Davis et al. (1998) assert that changes in the sex ratio at birth may represent a *sentinel health event* and that SRB could serve as a replacement for infant mortality as a measure of the health of a human population. A sentinel health event is recognized as any unusual pattern of disease, disability or mortality that warns of the need for preventative or therapeutic medical care changes at the societal level (Rutstein et al. 1983). Thus, study of the human SRB is salient not only because it contributes to an understanding of human biology, but because it may serve as an important early indicator of external stressors or underlying health issues in a population, if the causes of its variation can be more fully understood. The effect of wars, famines, economic conditions, demographic shifts, climate, and ecologic disasters have been studied in conjunction with SRB to understand more fully the evolutionary ecology of human populations. Helle et al. (2009) attempted to measure the relative effect of such events on the annual sex ratio at birth in Finland from 1865–2003. They found a significant increase in male births during World War II and during the warmest years, but no relation between SRB and economic development, famine, brief civil war and total mortality rate. Thus it appears the SRB in human populations may be subject to environmental forcing, making it a critical field of study for geographers.

Geography of the Sex Ratio at Birth

Little has been said about the geographic nature of the US SRB decline. The decline in the U.S. SRB and the Canadian SRB was first noted by Allen et al. (1997), who observed only broad geographic trends. The overall Canadian SRB, they found, had declined since 1970, with the greatest decline in the Atlantic region. They did not find a similar east-to-west gradient of increasing SRB in US Census regional divisions, although they found apparently significant differences among these divisions. Marcus et al. (1998) confirmed that the U.S. SRB had indeed declined significantly, from 51.3 percent in 1969 to 51.2 percent in 1995, but also observed that the SRB *increased* among black newborns. Because of reported similar national trends in Canada, Japan, and some European nations, this trend was considered important. Within each of the nine geographic regions of the U.S., they found that the white birth ratio declined and the black birth ratio increased during this period, except for a decrease in black SRB in the Pacific region.

I have plotted the SRB values for white births at five-year intervals from 1980 to 1995 for each of the nine standard US Census regional divisions on Figure 3. The lowest SRB in seven of the nine divisions was in 1995, the latest year of this period, suggesting a geographically widespread and progressive decline in the SRB throughout the US. However, it also appears that the white birth SRB in the East South Central subdivision (Kentucky, Tennessee, Alabama, Mississippi) is consistently higher than in other divisions, while the Mountain and Pacific divisions consistently report lower values. Understanding the decline in US SRB must also consider the possibility that there are stationary geographic areas of high or low SRB.

In studies of SRB in the US, geographic information is typically presented anecdotally without any ecological inference about the possible determinant nature of *where* a birth occurs. On a broader geographic scale, Grech et al. (2000) found that the SRB decreases in Europe as geographic latitude increases: SRB is higher in southern Europe than in northern Europe, with three latitudinal bands of change consisting of southern European, central European, and Nordic countries (Figure 4). However, the same researchers (Grech et al. 2003) found an opposite latitudinal effect in North America during a similar, but not coincident period of time: the national SRB was lowest in Mexico, with a higher one in the US and the highest in Canada (Figure 5). In a global study of 202 countries, Navara (2009) found that latitude is “a primary factor influencing the ratio of male and females produced at birth.” The SRB in tropical countries was 51.1, significantly lower than the 51.3 in countries with temperate and subarctic



	New England	Middle Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
× 80	0.5132	0.5136	0.5133	0.5144	0.5148	0.5169	0.5147	0.5123	0.5141
◆ 85	0.5128	0.5142	0.5141	0.5142	0.5148	0.5156	0.5123	0.5136	0.5120
■ 90	0.5139	0.5135	0.5131	0.5126	0.5141	0.5170	0.5110	0.5110	0.5128
△ 95	0.5122	0.5130	0.5126	0.5113	0.5149	0.5147	0.5121	0.5108	0.5113

Figure 3. Male proportion of white births by US census division, 1980, 1985, 1990, 1995. Legend symbols for each of these years are arrayed by column.

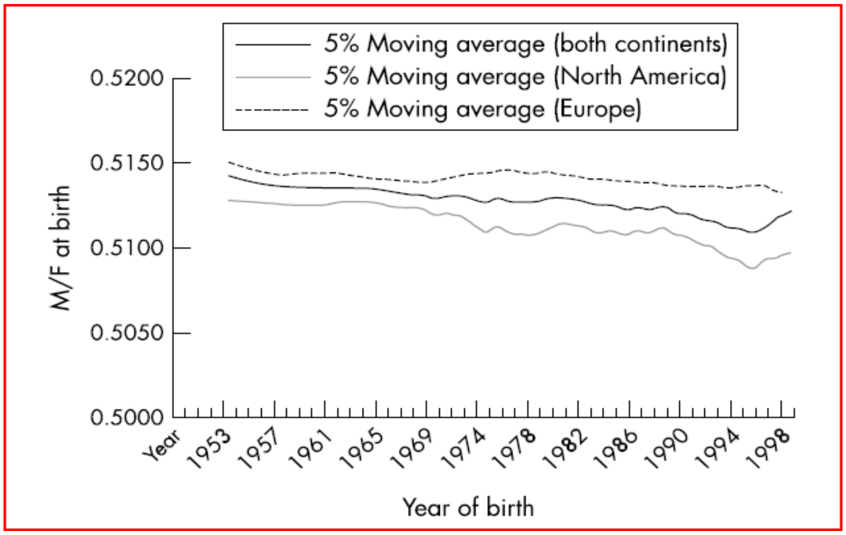


Figure 4. Male/Female (M/F) proportions for Europe (combined), North America (combined) and both continents combined (reproduced from Grech et al. 2003).

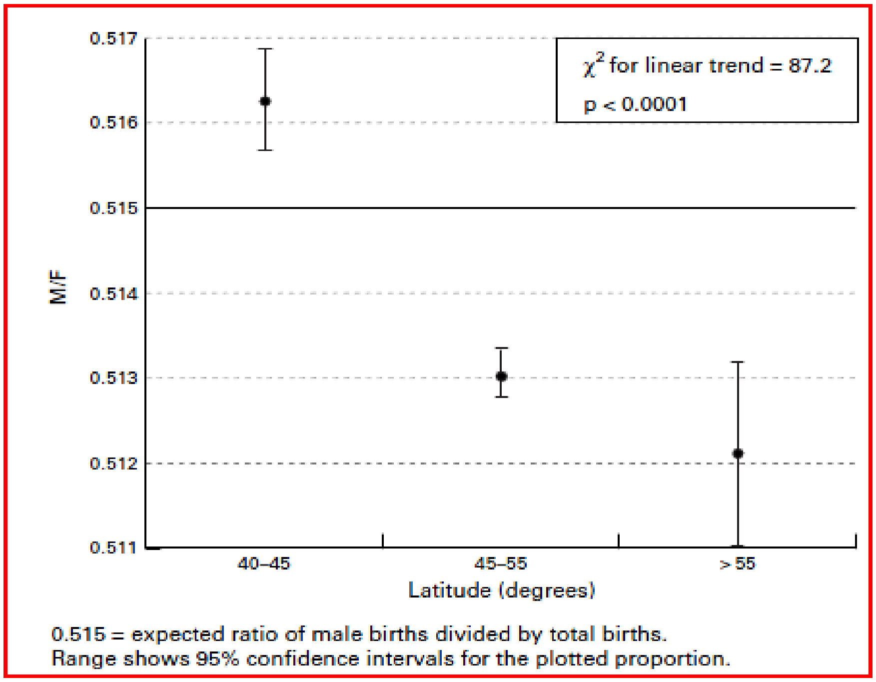


Figure 5. Ratio of male births to total births by geographical latitude in Western European countries for the period 1990–1995 (reproduced from Grech et al. 2000).

climates. Eighteen of the 20 lowest national SRBs were in the tropics: women living close to the equator tend to give birth to more girls (Figure 6).

The association of latitude and SRB is thus inconsistently reported to both increase and decrease with latitude, although control for cultural and socioeconomic factors varies among these studies. Grech et al. (2003), for example, did not address how socioeconomic differences between Mexico and the US might partially explain why the North American SRB gradient across latitudes was opposite of the European one. In addition, none of these broad latitudinal SRB studies addresses how climate, a suspected cause of latitudinal SRB variation, might vary within the same latitudinal band.

Both daylength and temperature have been implicated in SRB latitudinal variation. Navara (2009) speculated that daylength and melatonin levels may be a factor in the lower SRBs she found in tropical countries, an effect that has also been found in some animal studies. SRB varied among northern European populations in response to temperature fluctuations during conception and gestation over study periods in the 18th, 19th, and 20th centuries (Helle et al. 2008, Catalano et al. 2008).

SRB and Environmental Stress

The impact of climate change on SRB is an emerging topic in both domestic animal and wildlife studies. Concern is most immediate for reptilian species, for which sex determination is temperature-dependent and not chromosomal. Significant temperature increases could cause severe sex ratio skews in these species toward females and result in population crashes because normal mating activities are disrupted. Such populations may not be able to evolve rapidly enough to counteract the consequences of rapid temperature change across their habitats (Janzen 1994). Climate related effects may also be significant for species with chromosomal sex determination. A study of Pacific elephant seal populations during the recent period of warming ocean temperatures found that population levels had remained stable but that the SRB had increased — this suggests that changes in SRB, rather than in fertility *per se*, may be a precursor to significant changes to populations under stress (Lee and Sydeman 2009).

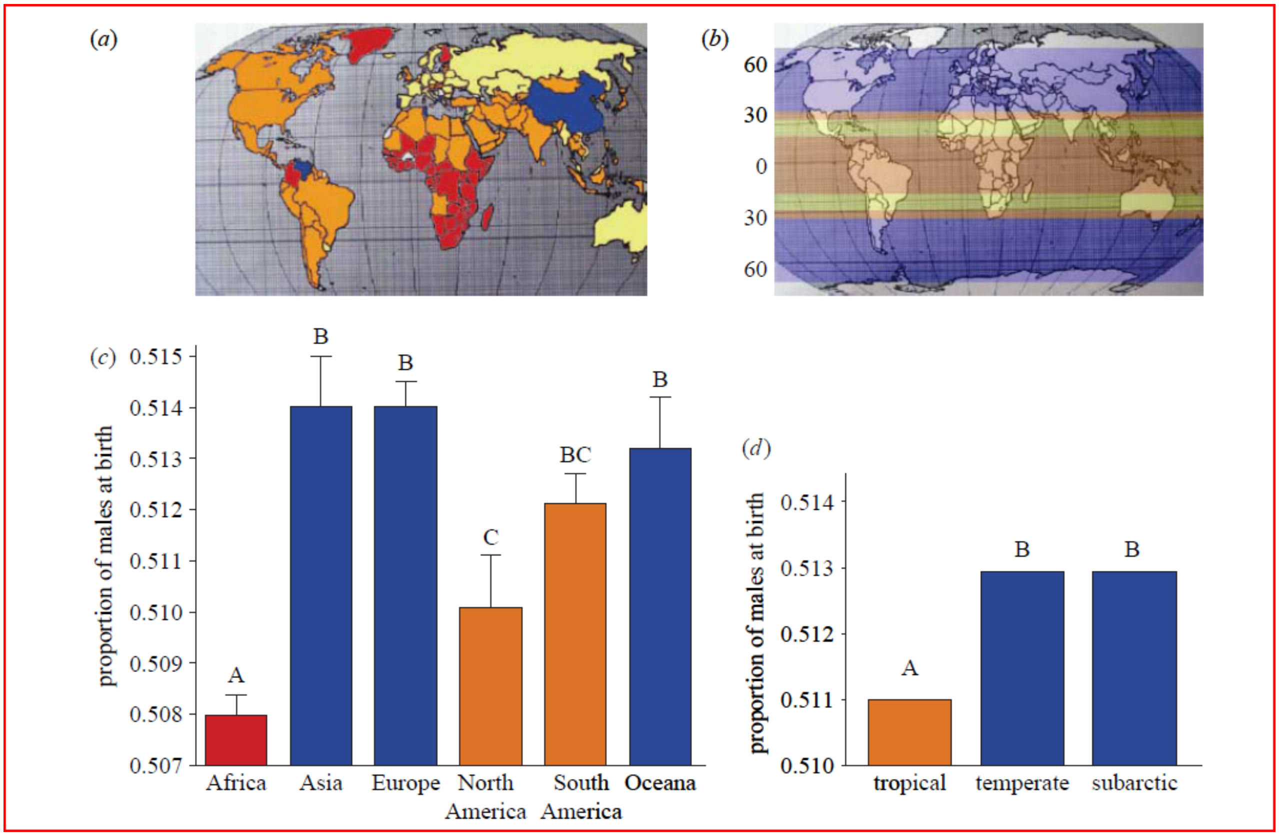


Figure 6. a) Visual depiction of average annual proportions of males at birth for individual countries 1997 to 2006. b) Color coded average proportion of male offspring [i.e.,male proportion] for each five degrees of latitude for 202 countries ranging from 0 to 65 degrees. c) Mean percentages of males at birth for countries according to continental location. d) Mean proportions of males for countries located in tropical, temperature or subarctic latitudes (F=11.07, p<0.0001, tropical-temperate and tropical-subarctic comparisons, p<0.01). All sex ratios were calculated using the average for 1997–2006. Figure segments are color coded (blue: more than 51.7 percent males; yellow, 51.2–51.7 percent males, orange, 50.7–51.7 percent males; red, 50.7 percent or less males. In (c) and (d), significant differences are indicated by different capital letters (reproduced from Navara 2009).

According to local resource competition theory, elephant seal mothers, who forage separately from fathers, will produce more males when sardines and other food resources favored by the species become scarce (a consequence of warming ocean temperatures), because male offspring leave their mother's care sooner than do female offspring.

The argument that SRB should be monitored in human populations as a possible signal of climate change stress was made by Catalano et al. (2008) in his study of the lowered SRB of late 19th and early 20th century Swedish mothers during extreme cold events:

> *The theory that natural selection has conserved mechanisms by which women subjected to environmental stressors abort frail male fetuses implies that climate change may affect sex ratio at birth and male longevity*.

Why human male fetuses may be more vulnerable to the environmental stresses of natural selection than females, while the opposite is true in elephant seals, is a complex question related to the evolved life histories of these species, the mechanism of which I will summarize in the literature review. My study examines the hypothesis that the evolutionary strategy of offspring sex allocation observed in many bird and mammal species continues to operate in human populations. Given that changes in patterns of temperature extremes and sex ratio at birth in the US have similar trends — both changing significantly at the beginning of the 1970's — it is reasonable to investigate whether changes in climate are a possible trigger of this mechanism, contributing to the recent decline in the US sex ratio at birth.

Research Questions

If an association between SRB and climate can be found, monitoring this association as climate continues to change is a critical item on the human health research agenda. It is clear that the US SRB varies geographically year by year (see, for example, divisional changes shown in Figure 3), although no consistent spatial or temporal patterns have been identified in the literature. The null hypothesis of this study is that this geographic variation of SRB is random. I test the hypothesis that US SRB varies in response to geographic regimes defined by climate when individual factors of SRB variation such as gestation length and plurality are controlled.

I have organized my research around three broad questions that attempt to answer questions about the significance of these factors and analytical approaches that might detect them.

1) Are monthly and seasonal climate aggregations at the US climate division level appropriate for examination of environmental effects on SRB?

Geographic studies of SRB have typically encompassed large units of observation such as the nation state (Navarra 2009) or even continent (Grech et al. 2002), areas too large for adequate consideration of the wide range of ecological factors that might influence sex ratio at birth. Both these studies suggest that latitudinal factors — daylength, temperature, or amplitude of seasonal variation — may be an influence on SRB, but both consider the US as a single data point in this analysis. The smallest geographic area for which SRB has been recently described in the US is the census region (see Figure 3), consisting of nine large groups of contiguous states (Allen et al. 1997, Marcus 1998). Beyond a description of the differences among these geographic regions, neither of these studies identifies any environmental component that would account for SRB variation among them. Further, just as demographic studies fail to consider geographically varying differences among the target population, geographic SRB studies have not sufficiently controlled for demographic factors of SRB. Possible influences of regional economic stress, extreme weather conditions, or other environmental or socioeconomic factors within an observed geographic area cannot be seen unless the birth order, race or origin, and plurality of individual births — all factors that may also affect SRB — are controlled in the analysis.

If too small a geographic area is selected, the idiosyncratic differences of individual places and unspecified factors within them may obscure the ecological effects of, for example, a climate regime across a larger geographic area. Further, the computational and analytic demands of examining data on too many observation units and variables preclude this approach, as does the problem of reducing the statistical power available to each of these small sample units. The collection scale of useful environmental datasets must also match the SRB unit of observation and such datasets at the neighborhood, zip code, or city level are missing for large portions of the US.

There are similar issues with the selection of temporal scale. Helle et al. (2008) found an association between SRB and annual temperature means but could not adequately explain the nature of the relationship because effects of seasonal changes were aggregated in annual values.

Birth records identify the day of birth and might be productively regressed on such data as daily high and low temperatures, but the computational burden of this approach quickly accelerates beyond practicality. For example, a model examining daily impacts of minimum and maximum temperature on births at the county level for a 20-year period requires 2 temperature values * 365 days * 3,140 counties * 20 years * n (number of variables of demographic values-1). Monthly values that are tabulated for many datasets across the study area may potentially isolate a seasonal or weather event-based variation with much less analytical burden than that of processing daily values. This study will address the question of whether spatial and temporal variation of SRB can be detected in response to monthly aggregations of climate measurements at the level of the US climate division.

2) Can logistic regression, geographically weighted regression, time series analysis, and spatial smoothing visualization be employed to detect spatial and temporal variation in US SRB?

The selection of spatially sensitive statistical analysis for this research is related to the question of appropriate ecological scale discussed above. Traditional multivariable parameter analysis of population dynamics for both human and wildlife studies have typically addressed the issue of spatial variation by ignoring it. Parametric analysis involved in logistic or linear regression models typically employed in SRB analysis assume that geographic units of observation are independent, an assumption that is violated by a hypothesis of SRB spatial heterogeneity based on environmental factors. Traditional SRB regression analysis may result in an error in specification of the degrees of freedom and a bias towards rejecting the null hypothesis, a Type 1 error (Haining 2003).

Recent demographic analysis and ecological population studies, however, have acknowledged the importance of the spatially explicit statistical model. This study uses a spatial model that accommodates the distribution of parental and biological individual factors (hereafter, "individual factors"), while creating a set of spatial residuals that may provide insight into geographic determinants of SRB. For example, the higher SRB among children born to white mothers in the East Central US census division relative to other census regions may be associated with variation in a specific urban/rural setting, climatic factor, or latitudinal gradient. Social and biological factors of each mother that might influence SRB must be controlled to the extent possible in order to detect geographic and temporal variation independent of these individual conditions and circumstances. This study will employ a combination of computational, visualization and statistical methods using both local and global models to determine the relationship of climate to SRB variation. Assessing temporal and spatial autocorrelation is used to diagnose potential error in modeling assumptions and can be used to construct a global model that is statistically defensible and of sufficient predictive and explanatory power to be used in future studies of SRB. Geographically weighted regression (GWR) is used in this assessment, but its autoregressive computational approach limits both the number of variables and number of geographic units that can be considered. GWR and other local statistics models also limit the use of logistic regression techniques which allow the consideration of demographic factors on an individual birth record while also evaluating both numeric and categorical environmental factors. Time series analysis is also used to assess seasonal roots and temporal autocorrelation but it suffers also from a restricted perspective of individual factors. Insights provided by charting and mapping relationships among variables are also used to understand geographic and temporal variation and to develop a final model.

3) What are the geographic and climatic associations of SRB decline in the US?

Studies of some animal populations support the theory of environmental determinants for sex ratio at birth, but results are mixed in human studies. Based on these studies, sunlight (photoperiod or light intensity), latitude, temperature and precipitation are potential determinants of SRB in humans. These effects are geographically complex, even within the limited study area of the contiguous US states. This study shows that these factors appear to influence SRB, although the nature of the relationship is less than clear due to this geographic complexity. These effects are also tracked as they change during the study period. Can regional differences in SRB be attributed to these environmental variables? Are effects the same in all demographic subpopulations or do they vary among these subpopulation geographically? Do temperature and precipitation effects vary according to latitude or climate regime type? Do effects correspond to predicted outcomes based on theories of environmental determination and sex allocation? Do these effects suggest a contributing cause to the decline in US sex ratio at birth?

Organization of the Dissertation

This chapter describes the often referenced decline in the sex ratio at birth in the US and makes the argument that the study of this decline in the context of climate change is a salient topic of research. This chapter also serves as a literature review of SRB decline and the relatively scant literature that examines geography as an essential but frequently overlooked component of SRB variation. Research questions are related both to the resolution of the specific relationship of SRB to climate change and the appropriate methodology for its discovery.

Chapter 2 reviews the literature associated with hypothesized individual and environmental influences on SRB. This review is highly selective, given the vast literature that has arisen in response to the early observation of the biological constancy of the sex ratio and the discovery of its variation among populations. This chapter seeks to organize SRB research by the findings most pertinent to possible climatic influence. I begin with those studies that describe some consensus about factors in individuals that cause variation of SRB. My review of spatial and temporal variation of SRB focuses on US births, although this literature is sparse and requires evaluation of SRB studies in other locations. Similarly, I consider seasonal variation of fertility and arguments about its relationship to sex ratio at birth. I describe evidence that environmental conditions at the time of conception may be significant influences on SRB and fertility, including those of temperature, precipitation, and daylength. The decline in US SRB is not detailed beyond the research described in Chapter 1, but I provide a summary of climate changes by US regional areas during the approximate period of the study. Explanations for SRB variation are framed primarily in terms the theoretical work of Fisher, Trivers and Willard, Maynard Smith, Price, Hamilton and others in the field of evolutionary biology who describe how the sex of an offspring is the result of reproductive fitness strategies adopted by its parents.

Chapter 3 describes the climate and birth data used for this study, including details on the data limitations and the judgments made to address them. The characteristics of the NCHS public use natality data is discussed in terms of its relation to the best available model of sex ratio variation that considers the social and economic status of each set of parents and their exposure to environmental factors. Assessments of these limitations are used to frame a geographically detailed model of US births in the lower 48 states for the period 1979 to 1988 (the geographic research dataset) and a temporally extended model of US birth in large counties from 1979 to 2002 (the time series research dataset).

This chapter also describes how candidate climate variables were refined for consideration in the final models using the US climate division as the primary geographic unit of observation and the calculated month of conception as the primary temporal unit of observation. Data quality and completeness for selected climate databases and their justification for inclusion is also discussed.

The geographic dataset and the time series dataset provide opportunities to explore spatial and temporal patterns of the US SRB during the study period using computational, visualization, and statistical methods. Chapter 4 presents results of the study of the geographic research dataset. I begin by describing the SRB and fertility patterns of the study period in the context of earlier US studies of these topics. Robust ordinary least squares (OLS) regression of univariate climate variables, OLS with spatial autocorrelation diagnostics, and cluster analysis are used to reduce the number of climate variables subjected to further analysis and control socioeconomic variables among the population studied. The geography of seasonal variation of the US SRB and birth rate is described by latitudinal gradients and in climate division maps of smoothed fertility and SRB rates. These variations are compared to likely associations with seasonally and geographically varying climatic factors for the 1979–1988 period and a GWR model of these associations is tested. Seasonality of estimated sex ratio at conception and birth rate at conception is examined using spectral analysis. The temporal and geographic stationarity of SRB during the 1979–1988 is evaluated and a logistic regression model of climate and individual factors is fit using this analysis.

Chapter 5 presents the results of study of the time series research dataset from 1979–2002. Latitude zones are used to compare geographic differences in trend. Time series forecasting tools are used to examine trends while accounting for seasonal and other autocorrelation factors. Demographic trends that have exerted both upward and downward trends on sex ratio at birth are examined. Changes in the patterns of seasonality are compared to changes in climate variables over the study period. I conclude by fitting a climate change logistic regression model of individual births and climate variables to control for these demographic changes for the period 1989–2001.

Chapter 6 summarizes the conclusions of the study and describes how its findings can be used to develop future models of variation in sex ratio at birth.

Chapter 2: Literature Review

Natural Selection and the Allocation of Sex Ratio at Birth

We must observe that the external accidents to which males are subject (who must seek their food with danger) do make a great havock of them, and that this loss exceeds far that of the other sex, occasioned by diseases incident to it, as experience convinces us. To repair that loss, provident Nature, by the disposal of its wise creator, brings forth more males than females.
[Arbuthnot 1710]

That the number of male births always exceeds that of females is well known to students of vital statistics, but the biological law responsible for the phenomenon has not yet been adequately determined though various theories have been offered in explanation.
[Russell 1936]

We uncritically accept that a one-to-one balance between males and females is optimal — it is the natural condition we see in our own species and in virtually all birds and mammals. But this parity is difficult to explain as a result of natural selection. Darwin spent a significant portion of *The Descent of Man and Selection in Relation to Sex* (1871) on this question. A better model, he speculated, would be a species of many females and few males, since the former are constrained by long pregnancies and the latter can produce sperm easily. He could not work out the evolutionary justification of a 1:1 sex ratio, concluding famously that the problem "is so intricate that it is safer to leave its solution for the future."

With the knowledge of genetic transmission that Darwin lacked, the statistician and population geneticist R.A. Fisher (1930) used metaphors of economic theory to explain how natural selection would favor gender parity. Fisher's theory begins with the general principle that sexual reproduction allows an individual to pass half of its genes (on average) to his or her offspring. For birds and mammals, reproduction is a significant "investment" (an economic metaphor favored in the genetic theory of the Fisher's time), involving not only mating, sexual intercourse, and pregnancy, but also nurture of the newborn, which is often the most significant part of the investment. Each individual thus makes an investment in his or her reproductive success that is only complete when the offspring becomes independent. This investment pays off when the offspring has produced offspring — poorly nurtured offspring will not thrive, mate, and produce “grand-offspring.” Since either a girl or a boy carry, on average, half the genes of either parent, either serves as well to produce the payoff of grand-offspring.

Given these basic genetic principles, Fisher theorized that natural selection favors an equal ratio of boys to girls in any population where the total cost of investment in offspring to the age of independence is equal for either a male or female offspring. His reasoning begins with the fact that all individuals are the offspring of only one male and only one female. In a population that was imbalanced towards one sex or the other, individuals in the rarer sex would have a reproductive advantage because, they would, as a group, contribute half the total genes of the next generation. Say that only 10 percent of a given population were females — the genes of these females would still make up half the total genetic pool of that population’s offspring. The tendency to have females, in this example, would be among the genetic characteristics contributed to the next generation. Females would thus naturally increase in relative numbers in each succeeding generation. If females became more numerous than males, then the same principle would operate to give parents of males a reproductive advantage, and so forth, until the population stabilized at parity.

Fisher’s model is generally accepted as the foundation of current evolutionary theories of sex allocation, the solution of the intricate problem Darwin bequeathed to future scientists. This model has been expanded and extended by several population geneticists and biological theorists since Fisher, including Hamilton (1967); Trivers and Willard (1973); Maynard Smith (1978); Charnov (1982); Bull (1983); and Karlin and Lessard (1986). In Maynard Smith’s terminology, the parity of sex ratio in most species is an evolutionarily stable strategy — it has been successful for the species as a whole and is not likely to be supplanted by mutant strategies that employ imbalanced sex ratios. The economic metaphors of Fisher’s original model have been replaced by equilibrium and strategy terminology in the game theory that now dominates thinking in this field. Extensions to Fisher’s model deal with its operation as part of varying life history strategies among species, and how individuals within a species might seek reproductive advantage by facultatively altering the gender of their offspring. Life history theory says that individuals of a species must allocate their time and energy resources between competing demands for growth, body maintenance, and reproduction, sometimes termed the *somatic vs. reproductive allocation*. In response to shifts in environmental conditions individuals may change reproductive strategies to take advantages of available resources and according to their individual condition.

Adjustment of Offspring Sex Ratio

Theory and data suggest that a male in good condition at the end of the period of parental investment is expected to outreproduce a sister in similar condition, while she is expected to outreproduce him if both are in poor condition. Accordingly, natural selection should favor parental ability to adjust the sex ratio of offspring produced according to parental ability to invest. Data from mammals support the model: As maternal condition declines, the adult female tends to produce a lower ratio of males to females.

[Trivers and Willard 1973]

These strategies differ not only among species, but between genders in a single species. Male deer must grow larger than females, for example, so that they can compete with other males for reproductive access and territorial defense. Thus, raising a male in this species to independence is a more costly investment than is raising a female, especially if the mother is not large or strong herself. This imbalance in costs between male and female offspring investment deviates from the assumptions of Fisher's original model explaining equal numbers of each sex. Thus, one shift in reproductive strategy available to a mother facing changes in environmental conditions might be to change the gender of the offspring she "chooses" to have. The possibility of sex ratio adjustment (facultative sex ratio manipulation) is well established in sex ratio theory. It operates according to the different life histories or social roles of each sex within a species. The "choice" involved is not one of forethought, but rather a biologically encoded and heritable physiological and endocrinal response of the parents to environmental stressors that skews production of one sex over the other. Trivers and Willard (1973) hypothesized that parents will choose to invest in the sex with the greatest reproductive payoff, in terms of grand-offspring, and that this investment may differ according to the parent's condition.

In general, an offspring from parents in poor condition will also likely to mature into an adult of poor condition. In a polygynous species like deer, a strong male will exclude all competing males and mate with all available females. This strong male has produced a bountiful reproductive return on the investment of its parents, passing their genes to the offspring of many females. Thus, deer in poor condition would make a better investment in a female offspring, which is only one of several females fertilized by the successful male, but a better risk than siring a weak male who may not mate at all. In their landmark studies of red deer on the Isle of Rum, Clutton-Brock and his co-researchers confirmed the Trivers Willard hypothesis — mothers in better condition produced relatively more males than did smaller, less robust females. They also found that during a period of drought, male proportions of births dropped throughout the population — more mothers were hedging their reproductive bets in the face of reduced forage by producing females (Clutton-Brock et al. 1986). Their work supports a principle that reproduction is less assured for a male than a female and that mothers will "choose" to pass their genes via female children when times are hard.

A sex allocation theory alternative to the Trivers Willard hypothesis is the differential mortality theory of sex ratio differences (Myers 1978). Males may simply be more fragile in the womb due to their larger size and a more complicated series of cellular divisions in their developmental sequence. Mothers facing difficult environmental conditions may lose male fetuses more easily. Natural selection is thus operating to cull the weaker individual, although very early in its development. Other alternative theories have been developed to challenge or extend the fundamental Trivers Willard formulation, including the partnership-status hypothesis, the "attractiveness" hypothesis, reverse causality, the "fixed phenotype" hypothesis, and the maternal-resource status hypothesis.

Several hundred studies have been conducted relating to the Trivers Willard effect itself; about half have produced significant evidence of these effects (Lazarus 2002). I do not propose to review the enormous literature of sex allocation theory in this study but I assert that it is well established in biological thought as a possible basis for explaining the apparently nonrandom variations of human sex ratio over time and place that I summarized in the introduction to this study. I will present here, however, a brief overview of evidence that 1) certain characteristics of individuals will predispose them to parent one sex or other, and 2) certain environmental conditions have been shown to bias the sex ratio at birth towards one sex or the other.

Accounting for the interaction of these two factors is the fundamental challenge of this study. I will particularly note studies of geographic SRB variation and the relationship of temperature and other climatic factors, photoperiod, and latitude on human SRB. If environmentally determined SRB in human populations can be conclusively demonstrated, it may shed light on how biological processes evolved during our Pleistocene ancestry continue to operate in our modern cultural milieu, in which our perception of climatic change is apparently more cognitive than physical.

Parental and Biological Factors in SRB Variation

I have adduced very large quantities of data to support the hypothesis that offspring sex ratio is causally associated with parental (including maternal) hormone concentrations around the time of conception.

[James 1996a]

That the SRB varies over time and geographically is well known; the suggested causes of this variation fill volumes. In the US, differences in SRB among races have been noted for many decades and remain the most consistent demographic factor in the variation in the US SRB (James 1994, Ruder 1985). Differences in SRB among race and ethnic origin groups in the US persist when adjustments have been made for age of parents, birth order, education, and marital status (Erickson 1976, Teitelbaum 1970). Many studies have attempted to explain these differences, which have been known at least since the early part of the 20th century. Winston (1931) found evidence of higher stillborn rates among U.S. blacks than among whites. He attributed this lower rate to the lower socioeconomic resources of the former group. He also attributed the birth order effect—the tendency towards female births as birth order increases—to the lower socioeconomic resources of large vs. small families. That is, as families grow in size, parents have consequently fewer resources and thus will produce fewer boys; this explanation for the birth order effect has not held up in subsequent study. Some workers have tried to equate reportedly low SRB in African nations with the low SRB reported in African Americans. However, Garenne (2002) found that SRB is as diverse in African nations as it is elsewhere, and some African populations, particularly some among higher socioeconomic groups in Nigeria and Ethiopia, have higher SRB than US white populations. Poorer nutrition, poor or missing medical care, and other attributes of lower economic status have also been attributed as possible explanations for lower SRB within some US populations defined by race or national origin. That the reason for these differences remains substantially unexplained despite many attempts to do so illustrates the complexity of SRB variation and the elusiveness of even its basic principles.

Part of this complexity is due to the collinearity among suspect factors and the difficulties of isolating maternal and paternal contributions. There appears to be strong support for, if not complete consensus about, the existence of an SRB birth order effect, related possibly to the condition of the mother. The later in the birth order a child is born, the less likely that it will be a boy. Some dissent to this principle exists; Jacobson et al. (1999b) did not find a significant univariate effect of birth order (or maternal age) on the SRB of 800,000 Danish births during the period 1980–1993. However, Erickson (1976) found that birth order was significant—but the age of either parent was not, once birth order was controlled for. Most authors have found that birth order is significantly associated with SRB either as a univariate factor or in combination with other factors. Lazarus (2002) found that higher birth order was significantly associated with lower SRB in 81 percent of 16 reviewed studies, increased paternal age was associated with lower SRB in 62 percent, and increased maternal age with lower SRB in six percent. Declining SRB has been found in association with increasing maternal age in combination with birth order (Juntunen et al. 1997, Orvos et al. 2001), and a maternal age effect has also been found independently of birth order (Ruder 1985). The relationship between maternal age and SRB may not be linear. Ulizzi and Zonta (1995) found that a function of the proportion of males among first-born children and mother's age was "a fairly good predictor" of the SRB in the wider population. James and Rostron (1985) found a curvilinear relationship between SRB and maternal age in England and Wales 1968–1977; Tarver and Lee (1968) also found that the relationship between maternal age and SRB was curvilinear in U.S. births, increasing sharply with age. The maternal age effect may therefore be more difficult to detect than paternal age and birth order because of its nonlinear relationship with SRB.

Multiple birth—also termed "plurality"—has been found to have a significant influence on SRB. The SRB of twins (both monozygotic—identical, and dizygotic—fraternal) is lower than that of singletons (James 1987a, Jacobsen et al. 1999b). The SRB for triplets is also lower than that of singletons (Jacobson et al. 1999b). The NCHS (Mathews and Hamilton 2002) also reported that the U.S. SRB of multiple births in the mid-1980s was lower (0.501) than that of singleton births; this difference was stronger among white births than black births. The relation of twinning rate to SRB has interested some investigators, particularly those seeking to explain racial differences in SRB. In general, the twinning rates of black populations in the U.S. are much higher than the twinning rates of white U.S. populations, although the gap has narrowed in recent years (Mathews and Hamilton 2002). One explanation for this may be the narrowing of the gap in prenatal health care quality among these populations in the US. Different twinning rates between white and black populations may also be present in other nations (James 1987a).

In a review of SRB literature in 1988, Chahnazarian offered a summary assessment of the "less than clear" relationship among individual factors that appears to still hold up in the majority of subsequent studies. Younger parents sire more boys, and there are more boys in lower birth orders. When both paternal age and birth order are controlled for in multivariable studies, maternal age weakens or is not significantly associated with SRB. The maternal effect also appears to decrease with increase in sample size. The effect of all these variables on SRB is small, and the stronger racial effect persists independently of other variables. To explain the reason for some individual factor effects, authors often note that increases in stillbirths are associated with increases in maternal age and birth order, and thus disproportionately increase the male fraction of prenatal mortality.

The general principle that males are a relatively greater burden to the mother and do not thrive as well in suboptimal conditions continues to be an organizing hypothesis in SRB research. The sex ratio at conception is believed to be higher than the sex ratio at birth and only 30 to 50 percent of conceptions result in live births. There is much evidence that males are costlier to the mother's health and future reproductive success. Males grow faster in the womb (Marsal et al. 1996). They are also generally heavier at birth (Loos et al. 2001). A study of US birth data shows mothers pregnant with boys have 10 percent higher energy requirements than those with girls (Tamimi et al. 2003). Although males and females begin in the womb with basically similar physiological forms, male sexual organs develop at the end of the first trimester and male development in general may consume more resources over the period of gestation than does that of females. Prenatal males may be, in general, more fragile than females, with a greater likelihood to be lost during development (Ingemarsson 2003). Mothers giving birth to males wait longer to produce their next child (Mace and Sear 1997). Single mothers produce fewer males than do two-partner relationships (Norberg 2004). All of these data suggest that producing a male has a higher reproductive investment cost than giving birth to a female. As workers in this field have noted, natural selection can operate on prenatal individuals as well as on those born (e.g., Catalano et al. 2008). One strategy to hedge the bet of producing the more expensive male would be to conceive and rear him in more optimum seasonal conditions.

Seasonal Breeding and Birth Rates

Seasonal variation in American births is one of the great demographic regularities which has never been convincingly explained, and only occasionally documented.

[Seiver 1986]

Many mammal populations show significant deviations from an equal sex ratio at birth, but these effects are notoriously inconsistent….One plausible explanation for the variation is that the mechanisms generating sex ratio variation are affected by environmental conditions.

[Kruuk et al. 1999]

Consideration of environmental determination of SRB in humans should include an understanding of seasonal breeding and the reproductive ecology of the Mammalia class. Negus and Berger (1972) identify two primary mammal reproductive strategies related to seasonal breeding, or seasonality. *Facultative* seasonality is an opportunistic approach to a climate that may vary unpredictably from year to year or season to season. Many desert species have evolved facultative breeding patterns that respond to the infrequent occurrence of rainfall. *Obligatory* seasonality occurs in more stable climatic environments and depends on hormonal decoding of environmental signals of upcoming seasonal events — predictive cueing. For example, certain obligate plant species absolutely require a night of appropriate duration — long or short — before flowering, and animal species dependent on them will similarly time their reproductive schedule. Seasonality may be affected according to the life history approach described by MacArthur and Wilson (1967) in which environmental conditions operate as selective forces to promote traits among species related to the quality and/or quantity of offspring. Certain species (*r*-selected) may have many offspring, relying on the likelihood that a few will survive, while others (*K*-selected) will have fewer offspring with higher survival potential. Opportunism, or facultative seasonality, is the preferred approach of *r*-selected mammals, those generally of small size and short lifespan that live in the tropics or seasonally unpredictable environments in higher latitudes. Predictive cueing associated with obligatory seasonality allows generally larger *K*-selected mammals with longer lives and gestation periods living in relatively stable climatic environments to time their mating so offspring are born into the most advantageous environmental regime (Bronson 1995). In higher latitudes, daylength is a predictive cue; in the tropics, where daylength is not as variable, the predictive cue is unknown (Bronson 2004). Humans are fundamentally *K*-strategists, but may employ different tactics along the r/*K* spectrum within and among populations. The demographic transition model of national birth and mortality rates is in some respects a description of the r/*K* strategy spectrum in human populations at the level of the nation state. Sex ratio at birth may be an ignored component of the classic demographic transition model. Using CIA national data, Dama (2011) found evidence in a multiple regression analysis that as human populations become more wealthy, life expectancy increases (R^2=0.80, p<0.001), total fertility is reduced (R^2 =-0.75, p<0.001), and more sons are produced (R^2=0.52, p<0.001).

The predictive cues that signal a favorable environment in which to give birth are food availability and quality, ambient temperature, and photoperiod, the organism's daily exposure to light. Indirectly, rainfall may also be a cue because it affects plant growth and the food chain dependent upon it (Bronson 1995, Alberts et al. 2005). Some ecologists combine factors of food availability with temperature to create an "energy balance factor" that might underlie the organism's perception of cues: caloric intake, energies expended in foraging, low temperatures. An individual or species must balance demands for energy between high priority activities to maintain cells, regulate body heat and find food, with lower priority activities like growth and reproduction (Bronson 1995). In any environment where resources are potentially limited, the somatic vs. reproductive allocation weighs more toward the former. Most mammals live in environments characterized by seasonal variations in climate and therefore food availability, so seasonal variation in reproduction has frequently evolved to match this variation. This variation may not merely extend to when offspring are born, but also to their sex. The facultative adjustment of sex ratio according to environmental conditions has been found in a number of species. Roche et al. (2006) found that dairy cattle adjusted the sex ratio of their offspring according to climatic conditions: more males were likely to be conceived when air temperature was higher and/or greater evaporation occurred, an outcome he attributed to the Trivers-Willard principle. Red deer studies found lower SRB during drought years (Flueck 2002).

Selective pressures occur on the late phases of the pregnancy when the female is limited in her ability to find food and in during the high energy requirements of lactation or the vulnerable period of weaning (Bronson 2004). In the temperate zone white-tail deer, for example, mating occurs in the fall, even though vegetative resources are rapidly waning. Birth, though, occurs in the spring when vegetation is abundant and ambient temperatures reduce the burden of thermoregulation. Calves are weaned by late summer when vegetation resources again diminish.

The most proximate trigger of seasonal breeding for humans could be the energy balance of food availability and thermoregulatory burden operating directly on hormonal controls (reviewed in Bronson 1995). In at least some mammals ovulation rises with levels of luteinizing hormone produced in the pituitary gland. Levels of this hormone are regulated by luteinizing hormone releasing hormone (LHRH), which is sensitive to the levels of glucose and other circulating fluids of fuels in the blood stream. If the levels of these metabolic fuels decrease, so do levels of LHRH, and, consequently, ovulation. Food deprivation can thus decrease ovulation and estrous activity in female animals (Wade and Schneider 1992), an effect that can be also be found in humans, as demonstrated by studies of woman who are anorexic or who are undergoing intensive physical training, such as ballet dancers (Abraham et al. 1992). Throughout a human population, the evidence for energy constraint as a factor in seasonal birth variation is mainly found in subsistence groups. Leslie and Fry (1989), for example, found in the nomadic and pastoral Turkana of Kenya a higher number of conceptions after the annual rains and the consequent rapid onset of vegetation, and a lower number during the late dry season, when woman are engaged in the physically demanding activity of daily water hauling. Females who suffer malnutrition also experience later onset of menarche and periods of lactational amenorrhea lasting two or three years, compared to a period of less than one year in more developed countries (Delgado et al.1992).

For the vast majority of populations in developed nations, lack of food cannot be considered an environmental constraint, but temperature may still exert a seasonal effect on reproductive seasonality (reviewed in Bronson 1995). Low temperature either alone or in combination with food availability is cited as a possible reason for the extreme seasonality of birth in North American Eskimo societies, but few examples of this influence in human populations are compelling. Humans have solved low temperature challenges primarily with cultural modifications; more problematic to human survival and comfort are high temperatures. High temperatures become a significant thermoregulation issue within a much smaller range of deviation than do cold temperatures. Heat may also influence human reproduction. Heat stress may delay the onset of sexual maturation, interfere with ovulation, and cause greater mortality in embryos and neonates (Bronson 1995). In humans, heat can suppress spermatogenesis and possibly testicular steroidogenesis (Levine 1999). Direct effects of heat on testis spermatogenesis are well known; men seeking to impregnate their mates know now to switch to loose fitting boxer shorts to improve sperm quality. Summer decreases in sperm numbers have been found (Levine 1999), but similar studies about heat affecting female conception rates are less well known. High temperature may have its greatest reproductive effect in terms of embryo survival prior to implantation.

Seasonal Human Endocrine Response

The controversy associated with claims of a biological basis of fertility and seasonality in humans is partly based on lack of understanding of how human reproductive physiology and endocrinology is keyed to seasonal events. Photoperiod had previously been discounted as a significant mechanism of human seasonality but recent studies of human endocrinology are changing this view. Navara (2009) attributes much of the global variation in SRB by latitude to photoperiod and speculates that melatonin is implicated in the reproductive processes that mediate seasonal SRB variation. Horton et al. (1989) note that photoperiod influences the sex ratio of meadow voles and reproduced this effect by injections of melatonin.

It is well documented that humans display physiological responses to the variations in daylight that occurs at high latitudes (Gern et al. 1987, Brzezinski 1997, Wehr 2001). Although located deep in the human brain, the pineal gland has a structure similar to the retinal cells of the eye and receives light signals and other inputs via the hypothalamus. Darkness induces the pineal gland to produce melatonin, while light inhibits this production.

Melatonin is synthesized and secreted by the pineal gland during the dark period of the light-dark cycle. With the onset of darkness, eye photoreceptors release norepinephrine, which activates production of melatonin in the pineal gland via the sympathetic nervous system; daylight inhibits its production. In addition to the eyes and the pineal gland, the circadian system employs the suprachiasmatic nucleus (SCN) of the hypothalamus gland, the so-called "biological clock" of the organism. The circadian clock located in the SCN generates endogenous pulses on a nearly 24 hour basis that sustain the rhythmic generation of melatonin. The SCN clock also receives inputs from the environmentally receptive pineal gland that trigger or correct its impulses. That the SCN continues to pulse to the pineal gland without environmental input has been demonstrated in deep cave studies of human volunteers isolated from clocks or environmental cues.

Changes in photoperiod are processed via the pineal gland, and melatonin operates in some manner to synchronize reproduction with seasonally changing energy balance conditions. In many organisms, melatonin is implicated in seasonal breeding as the signal of an appropriate daylength for beginning a gestation that will conclude at an optimum rearing time of high resource and energy availability. Melatonin is also implicated in hibernation, metabolism regulation and a number of other physiological functions and processes related to the overall functioning of circadian rhythm, the roughly 24-hour cycle in which these processes are timed

(Brzezinski 1997). In general, current research suggests that the neuroendocrine anatomy of melatonin encoding of photoperiod reproductive response that is present in other mammals also appears to be intact in humans and may affect the production of sex steroids in both human males and females. (Yie et al. 1995, Brzezinski 1997, Wehr 2001)

Photoperiod is probably not the only seasonal signal involved in melatonin secretion and other factors of human reproductive physiology but there remain significant gaps in knowledge about how this system works.. Melatonin may orchestrate the endocrinal changes that are responsible for seasonal variation in offspring sex ratio of humans and other mammals. Information about environmental conditions received through various senses is sent to the hypothalamus, which regulates the actions of the pituitary and adrenal glands (the "HPA axis"). The gonads respond to HPA axis signals and produce feedback. Pituitary gonadotrophic hormones, including luteinizing hormone and follicle stimulating hormone, stimulate ovulation, the maturation of germ cells, and other reproductive processes. These are carried through the blood to the gonads to regulate the production and secretion of gonadal or steroid hormones, primarily testosterone in males and estrogen and progesterone in females. James (1996a) has amassed a large body of evidence to show that the sex ratio of human births can be significantly influenced by conditions that change parental hormonal levels at or near the time of conception. He proposed that a high level of maternal luteinizing hormone at the time of conception is associated with an increased likelihood of a female birth, while high levels of maternal estrogen and testosterone have an opposite, but weaker, effect. In humans, gonadotropin receptors also appear to vary seasonally, with higher values in the winter (Luboshitzky et al. 1997). Seasonal variation in human reproductive ecology is not limited to fertility and sex ratio, but also to such traits as menstrual disturbances, recurrent abortion, proneness to twin pregnancies, and pathological pregnancies (Jongbloet 2003).

Human Seasonality of Fertility and Latitude

In spite of the many social influences on timing of conceptions, we conclude that the seasonal component in human reproduction is based on biological factors.

[Roenneberg and Aschoff 1990a]

While physiological mechanisms related to seasonal resource availability may not be relevant in most modern human populations, changes in temperature, rainfall, photoperiod and other environmental effects may persist as cues for hormonal changes formerly useful in adaptive reproductive strategies. Humans are not considered seasonal breeders by some ecologists, but seasonal variations in both fertility rates and SRB have been found, although the literature on the relationship between fertility and seasonality is far larger. In the most comprehensive study of global variation in human fertility to date, Roenneberg and Aschoff (1990a) found rhythms of seasonal variation in human fertility in all populations of 166 areas of the globe in a study that covered 3000 years of monthly birth data and 10 x 10^{10} births beginning in 1669. They described these rhythms in terms of the time of year when conception rates are highest, the length and slope of this high conception period, the amplitude of the annual pattern (maximal positive and negative deviation from means), the number of these maximum peaks (one major peak (unimodel) or a major and minor peak (bimodal)), and the phase of the steepest increase in annual rates.

In this and other studies, the seasonal pattern of births in the US was distinct compared to the rest of the world. Until 1934, a bimodal pattern with above mean fertility beginning in the spring predominates; thereafter an autumnal pattern with a peak near the autumnal equinox is dominant. The seasonal amplitude in US births is also lower than in most of the rest of the world. Beginning in the 1960s, Japan, the rest of the Americas, and several other nations show a migration towards the "US pattern" of low amplitude, autumnal-peak births. Lower amplitude predominates among industrial countries, and becomes a characteristic pattern as a country becomes more industrial. Figure 7, for example, demonstrates how the low amplitude of US birth rates was being matched by that of Japan and Spain as the 20th century progressed. The relative lateness of Japan's industrialization compared to Spain or the US is reflected in its greater birth rate seasonality at the beginning of the century. Associated changes in marriage patterns and other cultural shifts are also part of this complex phenomenon.

These authors also found differing conceptions rates within developed countries that also may be associated with the insulating effects of industrialization. Within nations, intra-society variations allow wealthier individuals to be insulated from seasonal effects and thus these

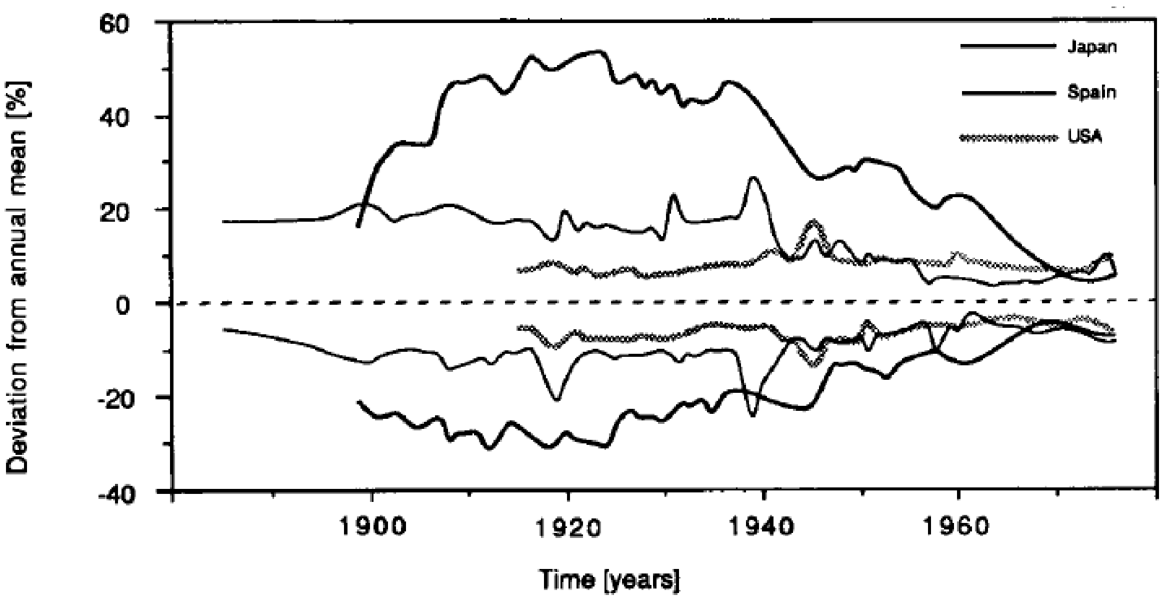


Figure 7. Decrease in seasonality of births in Japan, Spain, and USA during 20th century, expressed as percentage of deviation of monthly rates from annual means (reproduced from Roenneberg and Aschoff 1990a).

individuals display a reduced amplitude of seasonal variation. Urban populations have lower amplitude and maxima that occur later in the year than do rural populations. Similarly, the seasonal amplitude of fertility is lower for married mothers than it is for unmarried mothers and, in the US, it is lower for white mothers than it is for black mothers.

They acknowledged that holiday calendars, marriage patterns, and other cultural impacts were responsible for some inputs to this variation, explaining, for example, why bimodal patterns could result from increased conceptions near Christmas time. In another example of holiday influence, Athanassena (1985) showed an association in variation in the date of Easter and the timing of the respective conception peak. One problem in distinguishing biology vs. sociology in these patterns is that the timing of traditional holiday celebrations are based on more ancient ones marking seasonal events such as the spring equinox and winter solstice. The month of the summer solstice, for example, remains a popular one for weddings in the US and elsewhere. However, the similarity in married vs. nonmarried birth rate rhythms suggests that month of marriage is not usually a major factor in seasonality. These researchers found similar patterns in seasonal variation occur throughout the world that had no common calendar of social customs.

The seasonality of fertility, which I will argue is associated with the seasonality of SRB, is strongly related to environmental rhythms, particularly temperature and photoperiod, in subtle and complex interaction with cultural adaption of social patterns of holiday and marriage customs and the products of industrialized society, such as climate controlled housing, which serve to insulate individuals from the consequences of seasonal change. Roenneberg and Aschoff (1990b) found a strong association between latitude and seasonality which they attributed to endogenous environmental factors by correlating annual rhythms of human conception rates with photoperiod, monthly averages of daily hours of sunshine, minimum and maximum temperature, and humidity. At higher latitudes they found a steep increase in human conceptions during the vernal equinox. They conclude that photoperiod and temperature can account for much of the latitude dependence, waveform, phase and amplitude variations in conceptions.

These authors concluded that the greatest amplitude in fertility occurs at 30 to 40 degrees northern latitude. Conception rates are above the annual mean at temperatures between 5 degrees and 20 degrees C, and conceptions fall when temperatures are extreme. In regions with cold winters and moderate summers, conceptions positively correlate with temperature increases. However, in regions at or near the equator, fewer conceptions occur as temperature increases, perhaps because excessive heat discourages coitus. The bimodal pattern seen in many annual birth rate waveforms can often be found where summers are hot and winters are cold. By itself, however, temperature does not appear to a widespread limiting factor in modern industrialized populations that have evolved cultural modifications to temperature extremes, but could combine to influence seasonality of births with other factors, one of the most important of which is photoperiod, the length of daily exposure to daylight (Roenneberg and Aschoff 1990b).

In addition to cultural insulation from temperature variation, part of the stability in conception patterns in industrialized nations can be attributed to the use of contraceptive pills, the so-called second demographic transition. However, in a similar worldwide study, Barber (2002) also found that fertility has a latitudinal effect and appeared to be suppressed by short photoperiods and low temperatures, after controlling for urbanization, population size and density, gross national product per capita, female literacy rates, and use of conception. Lam and Miron (1991) reviewed fertility and environmental influences in a study of similar spatial and temporal scope to that of Roenneberg and Aschoff (1990a) but discounted the influence of photoperiod hypothesized by the latter authors because conceptions peak in the spring and summer in northern Europe, while winter is the highest peak of US conceptions. These authors (Lam and Miron 1987) earlier found a distinct latitudinal component in US births, with increasing amplitude in the southern portion of the county (Figure 8). A study by the US Division of Vital Statistics (Rosenberg 1966) also weighed in on the subject of birth seasonality, confirming that a spring trough and autumn peak existed in both white and nonwhite births, with a significantly greater amplitude of seasonality in southern US births (Figure 9).

Roenneberg and Archoff (1990b) suggested that the hot temperatures of North America compared to Europe overrode the effects of photoperiod. While warmth may be a signal of favorable conditions for conception, too much heat can have a depressing effect, as Seiver (1985) found in a review of US birth seasonality.

Backdating the monthly pattern of births between 1947 and 1976 by nine months, Seiver speculated that the trough of conceptions in July and August corresponded to the heat and humidity of those months and was especially pronounced in the southern US. He found that this trough tended to lessen towards the end of the study period, which he attributed to the widespread use of air conditioning, a significant cultural modification to US birth patterns.

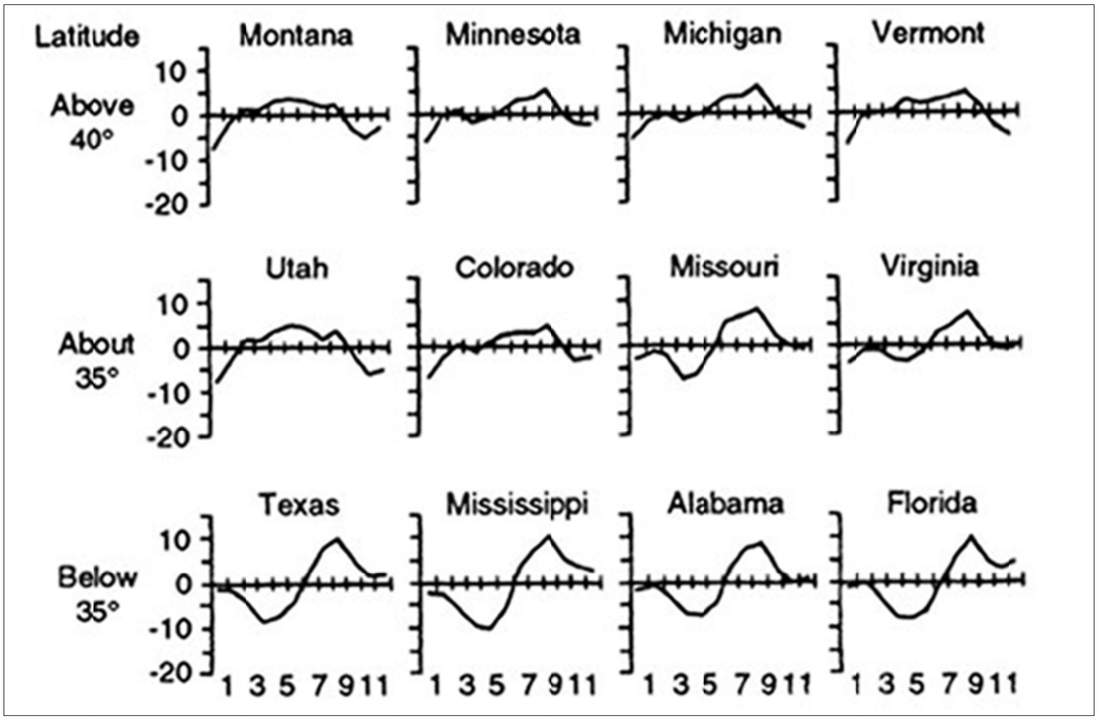


Figure 8. Regional variations in seasonal birth rates in the selected U.S. States (reproduced from Bronson 1995, using data from Lam and Miron 1987).

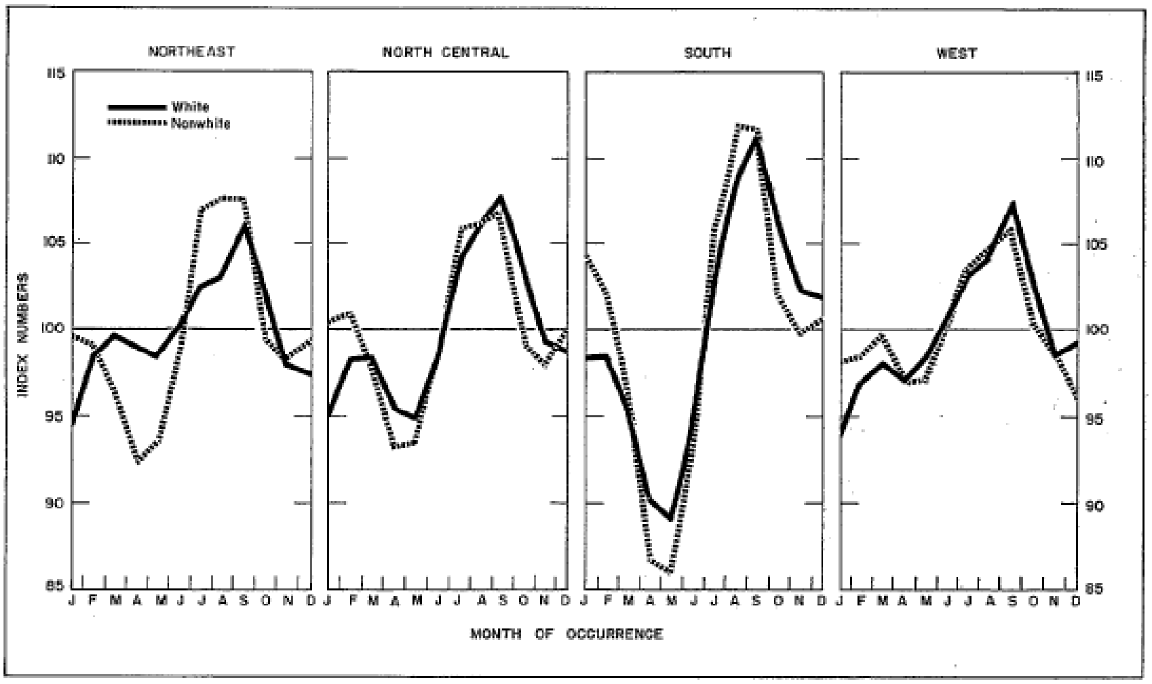


Figure 9. Average seasonal indices based on standard deviations for US white and nonwhite births for major geographic regions 1954–1963 (reproduced from Rosenberg 1966).

Cummins (2002) presented data in support of a hypothesis that increased environmental *light intensity* correlates strongly with increased conceptions, and that reduced light intensity in the form of clouds will counteract the effects of longer day lengths. He hypothesized that seasonality differences between U.S., Canada, and Europe could be explained by both the difference in photoperiod and light intensity at different latitudes, and to distinct seasonal cloud patterns between northern Europe, Canada and the southern US: the higher latitudes of northern Europe are cloudier than the U.S. and their sunny periods do not occur at the same time of year. The similar differences in the seasonality of SRB between Europe and the US described below might also be related to the combined factors of temperature, photoperiod, and light intensity that vary within the same latitudinal gradient.

Seasonal, Temperature and Latitudinal Variations in Human SRB

Here, data collected from 202 countries over a decade show that latitude is a primary factor influencing the ratio of males and females produced at birth…This pattern remained strong despite enormous continental variation in lifestyle and socio-economic status, suggesting that

> *latitudinal variables may act as overarching cues on which sex ratio variation in humans is based.*
>
> [Navara 2009]
>
> *Both the absolute temperature and — more markedly — the monthly temperature deviations from the overall mean were significantly positively correlated with the SRB ($P<0.01$) when temperatures were time-lagged against the SRB data by -10 or -11 months. It is concluded that the sex of the offspring is partially determined by environmental temperatures prior to conception.*
>
> [Lerchl 1999]

While research has confirmed the presence, if not the cause, of seasonal fertility in human reproductive ecology, literature about the seasonal variation of SRB is much sparser and less convincing. One hypothesis of my study is that fertility and sex ratio both respond to similar seasonal factors, but that sex ratio response is more variable due to the facultative gender strategy each individual mother adopts. To some degree, the issue of SRB seasonality is less complicated than that of fertility seasonality because the timing of conception can be largely controlled by contraceptives. The gender of births is not under this control, nor is there evidence that gender preference among US parents has significantly influenced the sex ratio at birth, although factors such as parental age at first conception, the number of children per family, and other demographic factors may have influenced changes in SRB. These factors can be somewhat controlled in analysis, however, so seasonal variation in SRB may be easier to attribute to purely environmental factors than is variation in fertility.

Navara (2009) speculated that lower SRBs in tropical countries than in higher latitudes were related to temperature or photoperiod, since she controlled for socioeconomic factors and cultural practices for sex-selection. Compared with higher latitudes, the higher temperatures and longer, less variable daylengths in tropical latitudes may result in differing levels of melatonin, which in turn may skew SRB. Colder, short-day conditions may be a signal to skew conceptions toward higher numbers of males born in the following spring and summer. In support of this theory, rodent studies have confirmed prenatal skews in sex ratio after melatonin injection (Gorman et al. 1994).

The tropics lack seasonality that is based on temperature and photoperiod, and warm temperatures in these lower latitudes may be tied to different environmental cues than among higher and more seasonal climates. Rainfall may be also a cue with varying effects across climate regimes. Lyster and Bishop (1965) found that human SRB in three Australian cities was influenced by seasonal variations in rainfall — more males were born 11 months after the rainy season. They speculated the cause lay in trace elements of drinking water that varied with alterations in rainfall and perhaps increased the availability of nutrients that favored male conception, but no direct evidence was found of this by the authors or in subsequent work. Drought and rainfall related effects on human SRB have not been studied in detail, however.

Temperature was found to be an important determining factor in two SRB studies in northern European populations. Helle et al. (2008) correlated annual SRB from the birth records of Sami peoples during the period 1745–1890 with reconstructed climate records to determine that more males were born in warm years, while more females were born in years preceded by warm years. A weakness of the study is that it fails to adjust for seasonality in birth records. Because the correlations were not based on monthly data, the relationship between temperatures at conception time and sex ratio could not be established with precision. In general, however, their results suggest that warm years signaled higher resource availability and a more favorable rearing environment that would support both mothers and their sons. The authors note that birth rates *per se* do not seem affected by temperature in this population, so the sex ratio may be a clearer indication of environmental sensitivity than fertility.

The corollary that fewer males would be produced in years of extreme cold was examined in a population of Danes, Finns, Norwegians, and Swedes born between 1878 and 1914 (Catalano et al. 2008). They found that not only were fewer males born during periods of lower ambient temperatures, but also that these males lived longer than those born at other times. The authors concluded that mothers did not bring to term as many males during these cold periods, but those that were born were more hardy as a group because they were the survivors of the prenatal culling of their cohort due to environmental stress.

Grech et al. (2003) examined sex ratio during the last half of the 20th century in both Europe and North America with a consideration for geographic factors. They found a highly significantly decline in both Europe and North America, particularly in Mexico, during this period. However, they found that male births declined in northern European countries (latitude greater than 40 degrees) during this period while rising in Mediterranean countries (latitude 25–40 degrees). The opposite latitudinal effect was observed in North America, with SRB increasing from Mexico to Canada, but this portion of the study was criticized because each of these countries encompass large variations in ecological conditions and because socioeconomic variation among these countries was not considered. Although Europe spans from 71 degrees N to 35 degrees N, most of it lies between 45 to 55 degrees N, while the continental US alone spans over 20 degrees of latitude.

A similar south-to-north gradient of decreasing SRB in three latitudinal bands in 27 European countries was also found by Grech et al. (2002), but two researchers (Voracek and Fisher 2002) noted that European countries with higher seasonal *amplitude* tended to have lower SRBs. That is, where temperatures were consistently warm or cold throughout the year, SRB was consistently higher than in areas which experienced greater variation in seasonal temperatures.

As noted in James' (1987a) comprehensive survey of the causes of variation in human sex ratio at birth, a number of researchers have failed to find an association between sex ratio and season of birth, while others have. Finding no evidence in relatively small populations were Pollard (1969), Strandskov (1942), Bochkov and Kostrova (1973), and Rantakaillio (1971). In a large population sample of all births in Germany between 1946 and 1967, Gilbert and Danker (1981) also found no significant seasonal variation in SRB. Others have detected SRB seasonality in small samples (Janerich 1971, Lyster 1970, Sarkar 1969, Timonen et al. 1965, Nonaka et al. 1991) and in large samples (King 1927, Takahashi 1952, Slatis 1953, Lyster 1971, James 1984b, Columbo 1957, Lerchl 1998, and Melnikov and Grech 2003).

Seasonality of US Sex Ratio at Birth

Some early researchers found no seasonality in US SRB. Ciocco (1938) found negligible seasonal influence on SRB in the US from 1925 to 1934 and Strandskov (1942) also found no variation of statistical significance for in US births for 1935. However, a seasonal pattern of SRB variation has been found in the US throughout the 20th century by several researchers. The most convincing early confirmation of seasonal sex ratio at birth variation in US populations was Slatis (1953), who undertook a study of approximately 60 million births occurring 1915 through 1936 and 1942 through 1948. While only a 0.25 percent difference was found among months, there was a statistically significant seasonal variation, with the highest proportion of males being born between May and July, and lowest between October and March (Figure 10). The SRB of spring/summer months (0.51412) was significantly higher than fall/winter births (0.51312) ($p < 0.0001$). He found a significantly high value in January, the fourth highest SRB month, exceeded only by summer births.

Slatis (1953) also attempted to explain geographic variation in the results. While the general seasonal pattern held throughout the US, a secondary peak in December, rather than in January, was found in the South Atlantic States (Delaware, District of Columbia, Florida, Georgia, Maryland, North Carolina, South Carolina, Virginia, and West Virginia). He concluded that geographic variation could not be compared between white SRB and black SRB, which were significantly lower, because three-quarters of black births during his study period were located in the South.

However, he found that both white and black births in South Central states (Alabama, Kentucky, Mississippi, Tennessee, Arkansas, Louisiana, Oklahoma, and Texas) had a higher SRB in January than in February or December. Urban areas in the northeast also had a secondary peak in January, while rural areas did not. In Boston, January has the highest SRB of any month. He attempted to correlate this secondary peak with the Lenten season and Easter but did not find a significant connection. However convincing the evidence of seasonality, he concluded that “no hypothesis appears to account for these facts.” The differences in SRB found by Slatis in cities with different latitudes and between urban and rural locations was the first research that confirmed the necessity of studying US seasonal SRB variation geographically.

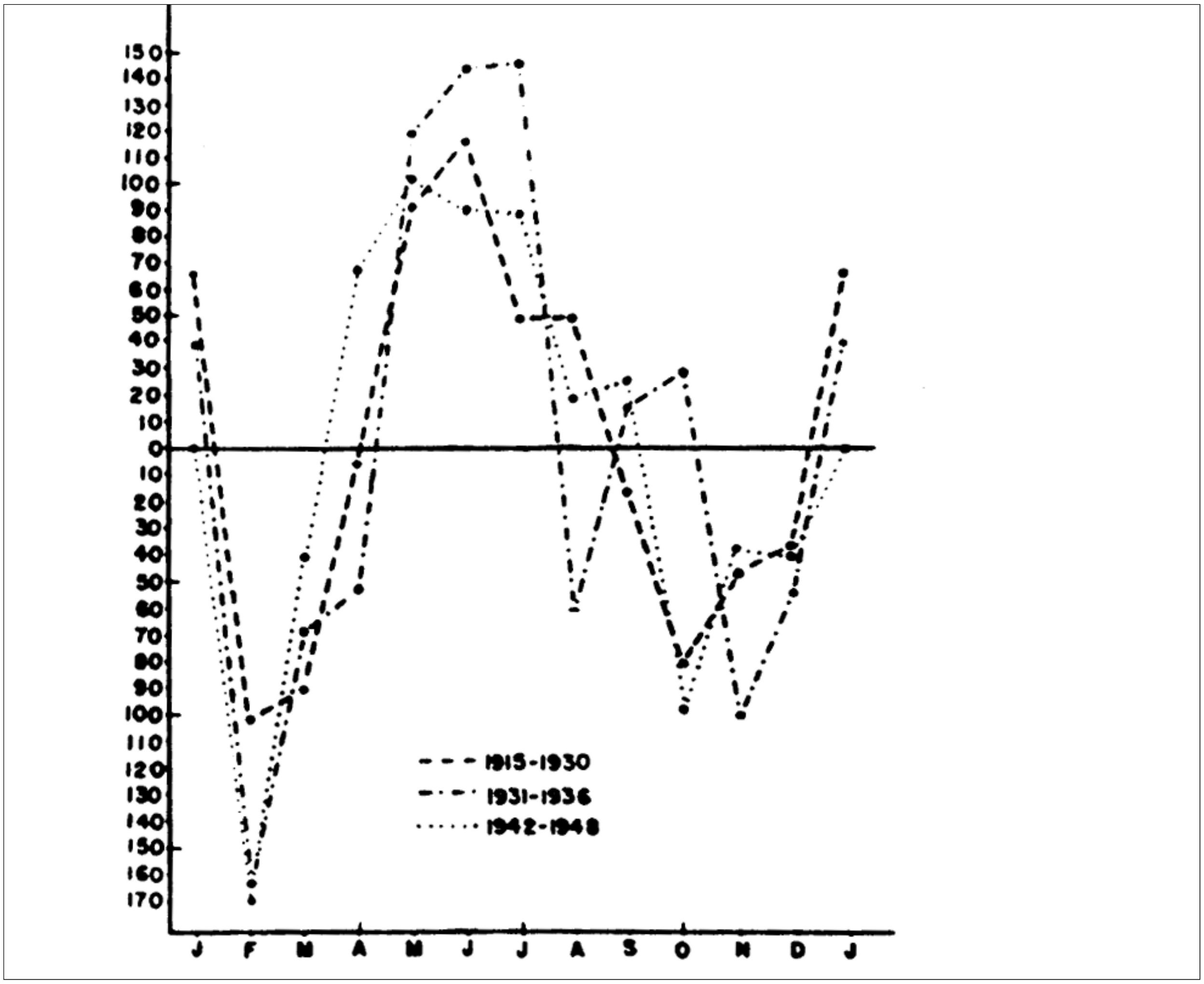


Figure 10. Monthly variation of U.S. sex ratio at birth, all births recorded 1915–1930, 1931–1936, 1942–1948 (reproduced from Slatis 1953).

Lyster (1971) studied the seasonality of both fertility and sex ratio at birth in US data from 1933 to 1970, unlike most earlier work which did not attempt to correlate the two. He compared 1964–1968 monthly fertility data with the monthly SRB from 1944 to 1968 and found seasonality in both, but noticed that the sex ratio peak lagged the birth ratio peak by two months (Figure 11). He found the same two-month lag between SRB and fertility rates in English and Welsh birth data from 1952–1968, although with different peak months.

The secondary December-January peak in US SRB noted by Slatis (1953) is not present in the 1945–1968 data Lyster examined. Lerchl (1999) found a bimodal SRB pattern when he reviewed 50 million live births in Germany over the period 1946–1995 (Figure 12). This is similar to the bimodal US pattern described by Slatis (1953), which disappeared after the 1940s. Unlike Lyster (1971), Lerchl (1999) did not find any correlation between birth rates and sex ratio.

The explanation for the seasonality of sex ratios must be sought in conditions at the time of conception, rather than at birth. Lerchl (1999) found that male births increased when temperatures were significantly warmer than normal in the 10th or 11th month prior to birth. Similarly, in study of births in a single Italian county from 1936–1998, Cagnacci et al. (2003) found no seasonal variation on the sex ratio at birth, but there was a significant seasonal rhythm to sex ratio calculated at the time of *conception*. More males were conceived in the warm months, presumably a signal of favorable reproductive conditions.

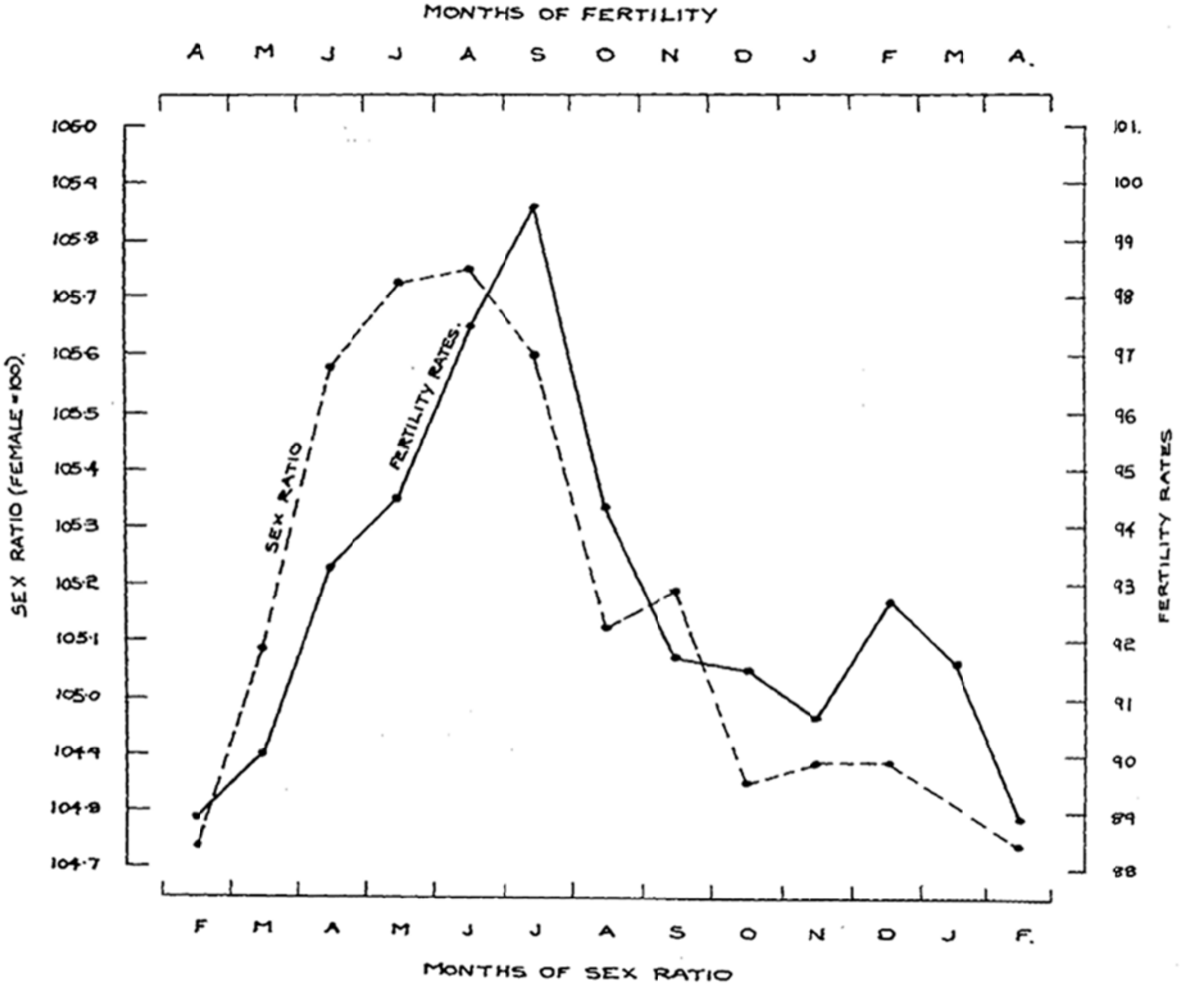


Fig. 1. Average sex ratios of live births (1945-1968) and average fertility rates (1964-1968), in calendar months.

Figure 11. Monthly variation in sex ratio of live births 1945–1968 compared to average fertility rates of women aged 18–44 for 1964–1968 (reproduced from Lyster 1971).

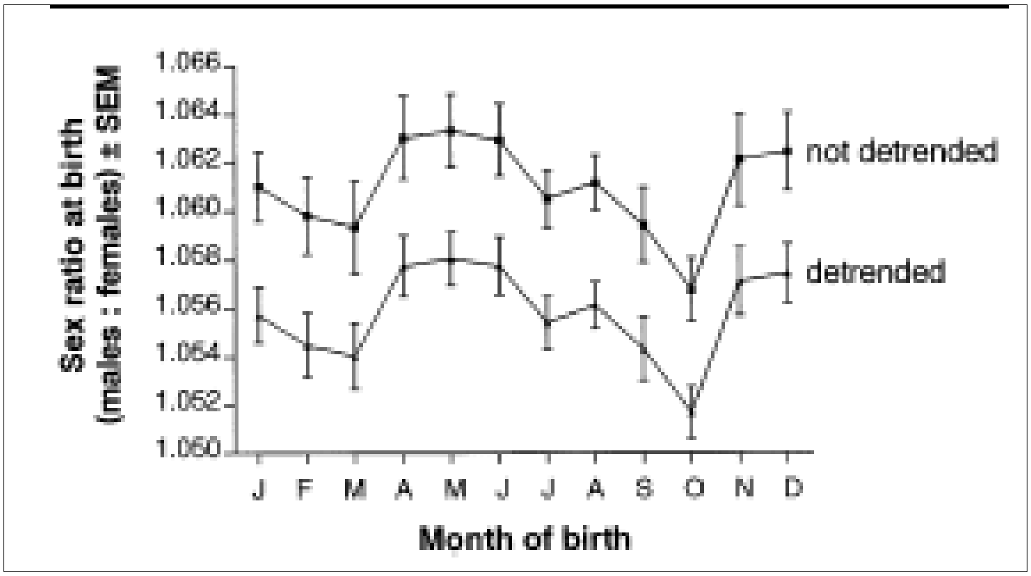


Figure 12. Seasonality of sex ratios at birth in Germany 1946–1995, with rates detrended for immediate post-war increase of births (reproduced from Lerchl 1998).

The possible latitudinal influence on SRB may not be limited to temperature variation and photoperiod cues. The incidence of Type 1 diabetes and of multiple sclerosis increases with latitude and researchers are examining these associations in both postnatal and prenatal populations. Vitamin D deficiencies in most of the U.S. population have been documented recently, a condition attributed to greater use of sunscreen use due to concerns about skin damage and also, perhaps, an increased cultural tendency towards indoor activities.

These deficiencies may also be a result of regional variations of the worldwide phenomenon of decreases in solar surface radiation (“global dimming”), a consequence of increased aerosol concentrations and changes in cloud patterns. The effect of Vitamin D deficiency in prenatal development is poorly understood, but Vitamin D may be critical in several initial developmental functions. For example, poor bone mineralization resulting from Vitamin D deficiency in the prenatal environment may disadvantage the male fetus more than the female one due to their different developmental schedules. In a recent study, Vitamin D levels among a cohort of infants born at the same latitude in North America were found to be significantly lower in African-American children (Basile et al. 2007). If further research shows that

Vitamin D deficiencies or other latitude-related health effects have an impact on SRB, perhaps by differentially impacting the development of healthy male fetuses, latitude and light intensity may operate as an environmental influence on SRB independent of its hypothesized predictive cue association.

Human SRB and External Stressors

Literature describing temporal variation in the secondary sex ratio among humans reports an association between population stressors and declines in the odds of male birth…. This work has led to the argument that population stress induced by a declining economy reduces the human sex ratio… This first direct test supports the hypothesis that economic decline reduces the human sex ratio.

[Catalano 2003]

The SRB of a population may decrease in the presence of economic stress (Catalano 2003), among those who are exposed to heavy smog events or floods (Lyster 1974) or earthquakes (Fukuda et al. 1998), or who live in active combat zones (Zorn et al. 2002). Stress may also be a factor in climatic related SRB influences, if such exist. Studies of mammal reproduction in the face of climate change imply that increasing warmth does not necessarily signal better resource conditions. External stressors may impact different sexes differently in each species, depending on the life histories and social roles of the sex. During years of weaker pressure differences and higher surface temperatures, for example, the food prey of northern elephant seals are reduced or dispersed. In these low resource years, more males are produced, possibly because adult males and females forage separately and female offspring present a greater resource burden (Lee and Sydeman 2009). When food resources became scarcer, as they are in the warming ocean temperatures where elephant seals forage, it is a greater burden for the mother to feed herself and her offspring. Because male offspring in this species will leave their mother earlier and disperse more widely than female offspring, stresses to food resources will result in fewer females because the mother will have to share her food with them for a longer period of time than with her male offspring. As Lee and Sydeman (2009) observe, this pattern confirms the local resource competition theory of sex allocation, which conflicts in this case with the Trivers Willard hypothesis that mothers in poorer condition will generally produce fewer males.

In general, however, animals subjected to heat stress may produce fewer males (Perez-Crespo et al. 2007). These authors noted that heat stress has deleterious effects on sperm quality, a condition that appears to result in significantly low SRB. Stressful environmental conditions may also impair sperm motility in humans, potentially promoting female-biased birth sex ratio (Fukuda et al. 1996).

Given the confounding demographic and cultural changes in the US population since the 1970s, the examination of possible environmental influences on SRB during this period is an extremely challenging task. However, several intriguing findings suggest possible environmental determination of SRB in human populations, although it is unclear what factors are the primary drivers and to which gender they skew the determination of offspring sex. If there is a significant relationship between SRB and environmental variables, the recent significant changes in weather-related factors associated with climate change should cause corresponding changes in the SRB. While increases in ambient temperatures should theoretically signal good resource conditions and a corresponding increase the proportion of male births, excessive temperatures may also trigger hormonal responses associated with stress.

Climate Change in the US During the Study Period

Ecological changes in the phenology and distribution of plants and animals are occurring in all well-studied marine, freshwater, and terrestrial groups. These observed changes are heavily biased in the directions predicted from global warming and have been linked to local or regional climate change through correlations between climate and biological variation.

[Parmesan 2006]

As I discussed in the introduction to this study, a number of studies have attempted to discover the cause of the decline in the US SRB in recent decades. Some have suggested that the decline is associated with increased exposures to environmental toxins, such as effect of pesticides on the male reproductive system (Møller 1996) or exposure of both sexes to endocrine disrupting chemicals (Davis et al. 1998). Studies of individuals with very high exposure to environmental toxins have shown that such exposure can significantly change SRB. Russian pesticide workers produced significantly fewer boys (Ryan et al. 2002), as did those exposed to dioxin after an explosion of a chemical plant (Mocarelli et al. 1996).

Differences in SRB in urban vs. rural populations have been found by some workers, an effect possibly associated with increased exposure to pollution in urban environments. Astolfi and Zonta (1999) suggested this cause when they found a lower SRB in the largest Italian cities compared to the rest of the county for births occurring 1970–1995. A convincing causal association between SRB change and typical residential level exposures to pollution of air and water has not been found, however. Lloyd et al. (1985) suggested that the high incident of respiratory illness, high SRB and air pollution in a central Scottish town were related, but Williams et al. (1995) examined the SRB in 12 Scottish communities near highly industrialized areas and found no significant difference in SRB compared to nearby communities without such exposure. In the latter study, the authors concluded that monitoring of SRB does not provide a reliable screening measure for detecting cryptic health hazards in the general residential community. No other study since has refuted that finding although work continues to fully assess the consequences of environmental toxins to human reproductive systems, not in only the form of changed SRB, but also in reduced sperm production levels, earlier maturation of females, and higher numbers of certain urogenital birth defects.

A potentially significant environmental shift experienced by US populations during the study period has been the consequences of climate change. For a summary of the regional changes in climate in the US, I refer to the US Global Change Research Program (USGCRP), which coordinates and reports the results of multiple federal agencies monitoring climate change in the US and elsewhere. This agency has documented significant changes in US annual temperatures, as well as US regional differences (USGCRP 2009). The USGCRP assesses climate change in six broad regions (USGCRP 2011) in the continental US (Alaska and the Islands are also studied), which I summarize briefly here.

In the Northeast, the annual average temperature has increased by two degrees F since the 1970s, with the highest rates of increase during winter months. Very hot days have increased in frequency and heavy downpours have increased. Less precipitation falls as snow and snowpack has decreased. Spring snowmelt and ice breakup on rivers and lakes occurs earlier.

The Southeast US is wetter and warmer than the rest of the US, but temperatures have still increased about two degrees F since 1970, with the greatest seasonal increase occurring during winter months. The number of freezing days has declined for most of this region since the 1970s. Fall precipitation has increased in most areas, except south Florida, where it has declined. At the same time, the incidence of summer and spring droughts of moderate to severe intensity has increased since the 1970s. Climate models predict a continuing trend of warming in this region, especially during the summer, and an even greater increase in the number of very hot days.

The Midwest is subject to continental climate and influences from the Great Lakes, causing typically large swings from very cold winters to hot, humid summers. Temperature increases since the 1970s have also been observed in this region, with the largest increases again in the winter months. Great Lake winter ice has decreased significantly in recent years. Driven by earlier dates for the last spring frost, the frost free season has been extended by one week. Very heavy downpours have doubled over levels recorded in the 19th century and two record-breaking floods have inundated the region in the last 15 years. Heat wave frequency has reached or exceeded the rate of the Dust Bowl years of the 1930s.

Like the Midwest, the Great Plains experiences strong seasonal climate variation. Paleoclimatological records confirm a long cyclical history of periods of long droughts alternating with wetter periods. Moisture patterns vary across the region, from semi-arid in the western portion to moister patterns in the eastern section, but precipitation has increased in all portions in the last several decades. Similarly, winter temperatures vary widely in this region, but have increased as in any regions of the US. The greatest temperature increases have occurred during the winter and in northern states. Relatively cold days are becoming more frequent and relatively hot days more frequent.

As defined by the USGCRP, the Southwest region includes the southern Rocky Mountains to the Pacific Coast. Some of the driest and wettest precipitation zones are encompassed by this region, which also has the greatest range of elevation. Recent climate history consists of usually wet periods during the 1980s and 1990s, especially in contrast with very dry periods in the 1950s and 1960s. The rate of warming in recent years in among the highest in the US, resulting in a significant decrease in spring snowpack, changes in Colorado River flow timing and strength, and disruptions in the region’s water cycle.

The Northwest has experienced somewhat less temperature increases than other parts of the US, about 1.5 degrees F over the past century, although some areas have increased up to 4 degrees F. Trends in decreases of summer precipitation and increases in winter precipitation have been documented and are expected to steepen. Earlier snowpack melt in the Cascades and other higher elevation areas has resulted from warmer fall and winter temperatures in the area. Cool season temperatures in the Cascades have increased 2.5 degrees F over the last 40 to 70 years.

While regional climate change dynamics are complex, some generalizations can be made about climate change across the US. Since US population is concentrated in urban areas, urban heat island effects are particularly worth noting. The USGCRP notes that this effect has raised average urban temperatures in the last 100 years by 2 to 5 degrees 5 over those in surrounding areas, and by up to 20 degrees F more at night.

These trends towards warming in all US regions are projected to continue. Cold season tracks will continue to move northward and the West will become even drier. Most of the US will experience greater increases in warmth in the summer than in the winter. Precipitation from warm air and moisture mixing patterns will move to higher latitudes than in the past. In general, precipitation will fall more often as rain than as snow compared to the past. The subtropical dry belt in the Southwest and other areas will expand as winter and spring precipitation decrease in these areas.

Possible Impacts of Climate Change on Human SRB

In addition to stresses on infrastructure and agriculture, a number of human health impacts are anticipated from climate change. These include heat stress, direct thermal injury and associated illnesses from increased temperatures; increased morbidity and mortality as a secondary effect as catastrophic weather events; and increases in the frequency, distribution and length of zoonotic and vector borne diseases, as well as water-borne and food-borne illnesses (Luber and Hess 2007). No research has been done to suggest that climate change has caused changes in the human sex ratio at birth, but recent research about the impact of climate change related effects on wildlife reproductive ecology suggest that it is a possibility. A fundamental question arising from this research is, are changes in human sex ratio at birth an indication of the biological consequences of climate change found in many plant and animal species? Many species face extinction and significant ecological trauma due to range shifts in latitude and altitude, disruption of natural communities, changes in physical structure or genetics, and phenological shifts — the change in timing and geographic location of critical life cycle events such as flowering and bird migration. Parmesan (2006) asserts that most observations of climate-change responses in species have been alterations of species' phenologies, in which a species has altered its long-established seasonal calendars of growth and reproduction to seek optimal conditions that have shifted in response to climate change. If human reproductive ecology has seasonal components, it may also be influenced by the earlier onset of spring, a lengthening of the vegetative growing season, and the increased occurrence of very hot days, warmer winters, and catastrophic weather. The time period of my study encompasses those events in US regional climates and seeks to explain their relationship to fertility and sex ratio at birth. In order to study such relationships, a suitable database needed to be constructed. That task is described in the next chapter.

Chapter 3: Materials and Methods

The research question depends on recent climate and birth data with sufficient geographic and temporal detail. Based on data availability, I chose births that were registered in the contiguous United States from 1979 to 2002 as the base study period due to data availability and quality. The quality and detail of birth data varies through this period and are subject to different methods of analysis based on this variation. Computational, visual, and statistical methods were used to determine the association of climate, spatial location, temporal trends, and other potentially influential factors on the sex ratio of birth. How these data were selected and analyzed is discussed in this chapter.

Climate Data

Climate Division Data

Previous geographic analysis of US SRB has been confined to large areas such as US census regional divisions or states. The size of these larger geographic areas does not allow for the identification of local varying factors of climate or other potential biological influences on the SRB. However, as the geographic unit becomes smaller, the statistical power problem magnifies. Because SRB varies only very slightly from year to year and location to location, large populations are required to register statistical significance by traditional methods. The number of births in several U.S. counties, for example, is less than 100 annually, with some totals registering in the single digits. Also, spatial dependence among units is expected to increase as geographic units become smaller.

The National Climatic Data Center (NCDC), operated by the National Oceanic and Atmospheric Administration (NOAA) of the Department of Commerce, divides the 48 contiguous United States into 344 climate divisions, which are generally considered climatically homogeneous regions. These divisions are the primary geographic unit of observation of the study. The climate division offers a manageable *n* of units for autoregressive local statistical analysis of US SRB, compared to the US county and county equivalent (3,140). The climate division is small enough to isolate local climatic effects, but large enough to create sufficient sample size.

Climate divisions number up to 10 per state and do not cross state boundaries. Within each division, temperature, precipitation and related or derived values of these two factors are aggregated from all reporting stations within the division and adjusted for observation bias and other error (Karl et al.1986). As such, the US climate division database is a consistent, aerially invariant, and serially complete database of climate variables estimated across spatially contiguous areas beginning in 1931, although with records for some areas begin as early as 1895 (NCDC 1994). Although these data are used for many climate studies, weaknesses in the data have been documented by some (Muller et al., 1990; Guttman and Quayle, 1996), particularly for long term studies. Complex terrain and a lack of reporting stations in some climate divisions, particularly those in the western US, weakens the assumption that a single aggregated value reports the climate experience for a selected individual within the division. For some historical climate research, an alternative NCDC historical database, the U.S. Historical Climatology Network (USHCN), provides high quality monthly aggregated historical temperature and precipitation data from 1,218 observing stations across the contiguous US. The USHCN is used, for example, to create rankings of record annual temperatures in the US. However, the USHCN does not attempt to interpolate climate values beyond the observing station location to a historically consistent set of areal geographic units.

For each climate division, the NCDC has calculated monthly means of temperature (degrees Fahrenheit (F) to 10ths) and precipitation (to 100ths of an inch). Monthly heating and cooling days are derived from temperature data and reflect energy demand for heating and cooling. A cooling degree-day, for example, is calculated when there is a 1-degree F difference between 65 degrees F and a mean outdoor air temperature of 66 degrees F, on any given day. A degree-day compares the outdoor temperature to a standard of 65 degrees F; the more extreme the temperature, the higher the degree-day number. Thus, degree-day measurements are used to describe the effect of outdoor temperature on the amount of energy needed for space heating or cooling and are useful as another way to consider the deviation of temperature in a given month from indoor supplied controls. Therefore, climate division average temperatures are positively correlated with cooling days and negatively correlated with heating days. Degree days approach zero when outdoor temperatures reach those that modern indoor heating/cooling systems are designed to achieve.

Four drought indices are included in the climate division data: Palmer's (1965) Meteorological Drought Severity Index (PDSI), the Hydrological Drought Index (PHDI), the Z Index, and a modification of the PDSI, referred to as the PMDI. According to NOAA, the main difference between the PDSI, PHDI, and PMDI is their treatment of the beginning and ending of droughts or wet weather periods — during the maximum severity of these events, the indices report identical values. The PDSI is a retrospective metrological drought index that attempts to classify spells of weather. It responds quickly to changes in weather regardless of changes in streamflow, soil moisture, lake levels and other hydrological conditions. The PHDI more closely reflects changes in stream flow and other hydrological values. The PMDI is considered a compromise between the PDSI and PMDI — it adjusts more rapidly than the PDMI to changing weather conditions. The Z index is a monthly standardized moisture anomaly index based on a standardized monthly water balance. It measures short term moisture conditions independently of previous or subsequent monthly values and reflects short term drought or wetness more distinctly than do the other indices. All these indices discount man-made droughts, such as the lowering of lake levels.

US climate division data are digitally distributed by NCDC (1994) in the Time Bias Corrected Divisional Temperature-Precipitation-Drought Index (TD-9640). Because climate conditions at the time of conception are required for analysis, I downloaded and coded for use the TD-9640 database for climate records from the website (NCDC 2010a) from each monthly period for the 25 year period 1978 to 2002 for the 344 climate divisions.

Monthly Divisional Normals and Standard Deviations

Climate measurements for any month could represent extreme deviations from normal values. To evaluate the effects of this deviation on SRB, I included normal monthly values based on longer term averages. NOAA distributes via the NCDC monthly climate division normals and standard deviations derived from primary divisional data (NCDC 2010b). Normal and standard deviation values for each of the 12 calendar months and an annual value are calculated for each division over several thirty year periods beginning in 1931. I used the 1971–2000 period presented in the CLIM85 version of this database as a baseline to compare monthly climate values for the study period. Monthly divisional average temperature and total precipitation data are derived using data from all stations reporting both temperature and precipitation within a climatological division. Monthly temperature normals and 70-year averages for each division are computed by adding the yearly values for a given month and then dividing by the number of years in the period. The annual normal is computed by adding all of the monthly normal and then dividing by 12. Precipitation normals are computed similarly, except annual values are the totals of the 12 monthly values. The data also include heating and cooling degree days using the monthly average temperature and its corresponding standard deviation to compute degree days.

Daylength

The number of daylight hours, the period between sunrise and sunset, is dependent on latitude and day of the year. I created a field for mean monthly daylength in hours using the midpoint monthly date and latitude of the each climate division centroid. This was derived from a simplified formula provided by Glarner 2009:

$$m = 1 - \tan(Lat) \tan\left(Axis \times \cos\left(j \times Day\right)\right)$$

where *m* is the exposed radius part between sun's zenith and sun's circle, *Lat* is the latitude of the centroid of the division, *Axis* is a constant value for obliquity of the ecliptic, *j* is a constant to approximate π/182.625, and *Day* is numeric day of the year using the winter solstice as day 0. I used the 15th day of each conception month, except the 14th for February, to calculate Day for each climate division. M is multiplied by 24 to calculate the number of hours of sunlight on that day, which ranges from approximately 8 to 15 hours over the year in the contiguous US, with a slightly smaller range in the lower latitudes.

National Solar Radiation Database

The National Solar Radiation Database (NSRD) was used to assess the potential effect of ultra-violet and other solar radiation on SRB. This database was produced by the National

Renewable Energy Laboratory (NREL) primarily to describe the geographic and seasonal opportunities for solar energy production in the contiguous US. NREL uses NOAA National Weather Service (NWS) data and NCDC climate data from the National Climate Data center. For this study, I used Release 1.0 of the database, which covers the period January 1961 through December 1990 (DOE/NREL 2010).

While the NSRDB time period suits the study, the geographic coverage is less than ideal. The NSRDB contains a total of 56 primary and 183 secondary stations distributed across the US. These are NWS locations that provided various data for solar radiation computations, but stations designated as secondary used modeled, rather than directly measured data. Monthly values for each year in the study period are calculated for three of the most common measures of solar radiation: including global horizontal radiation in Wh/m2 (atmospheric pressure in millibars), direct normal radiation in Wh/m2, and diffuse horizontal radiation in Wh/m2. Indirect measures of radiation at a lower quality level than these include total sky cover in tenths, opaque sky cover in tenths, and aerosol optical depth. Other meteorological data are also included in the NSRDB database, such as temperature and precipitation which are already present in the TD-9640 at a better spatial resolution, but I did include humidity and wind speed data from NSRDB records.

County – Division Boundary Differences and Attribute Matching

Climate division boundaries in the eastern US generally conform to county boundaries, making assignment of climate values to county of residence fields in registered birth records a relatively simple task in these areas. This is less the case in the western US, where watersheds are used to delineate division boundaries. Some counties may cross two or more climate divisions, although no climate division crosses a state line. To assign birth records to climate divisions in these areas, two spatial join methods available in ArcGIS 9.3.1 GIS software were used. First, an ESRI ArcInfo export coverage format (*.e00) file was downloaded from a USGS Water Division ESRI Coverage of the 344 contiguous US climate divisions (USGS 2009) and converted to a ESRI shapefile format with a USA Contiguous Equidistant Conic projection in ArcGIS 9.3.1 Software[2] (ESRI 2009). This projection preserves distances along all meridians and one or two parallels. For geographically weighted regression, preservation of scale at certain distances is preferred over projections that preserve direction, size, or shape. A shapefile of US 1990 county boundaries was created from archived census data products maintained by Columbia University (2009). Where the climate division boundary used county boundaries, a shapefile of county centroids was joined to the polygon shapefile of the climate division using the ArcGIS spatial join method. For the second case, where county boundaries did not form the division boundary, I assigned the birth record to the division in which the largest percentage of the county population fell. To determine this, I assigned the county FIPS code and total 1990 census block group population to the centroid of each census block group using data from the Columbia University archives. These centroids were spatially joined to climate divisions and each county assigned to the climate division in which the summed population of county census block groups was highest. In most cases, the centroid of the county falls within the climate division polygon. Appendix 1 lists the 82 counties that were not assigned to the climate divisions within which the county centroid fell using this block weight method. Based on this method, five of the 344 divisions were not matched to any county, so were excluded from the study area.

To relate NSRDB point station data to birth records, I created a point shapefile for each NRDSC station and joined it to a point shapefile of divisional centroids. Climate divisions were assigned the NRDSC of the closest station. No distinction was made in this assignment between primary and secondary stations. Figure 13 shows the location of the NSRDB stations and division boundaries. The five climate divisions in dark green are those omitted from the study database based on the county assignment technique described above.

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[2] False_Easting: 0.000000;False_Northing: 0.000000;Central_Meridian: –96.000000;Standard_Parallel_1: 33.000000;Standard_Parallel_2: 45.000000;Latitude_Of_Origin: 39.000000)

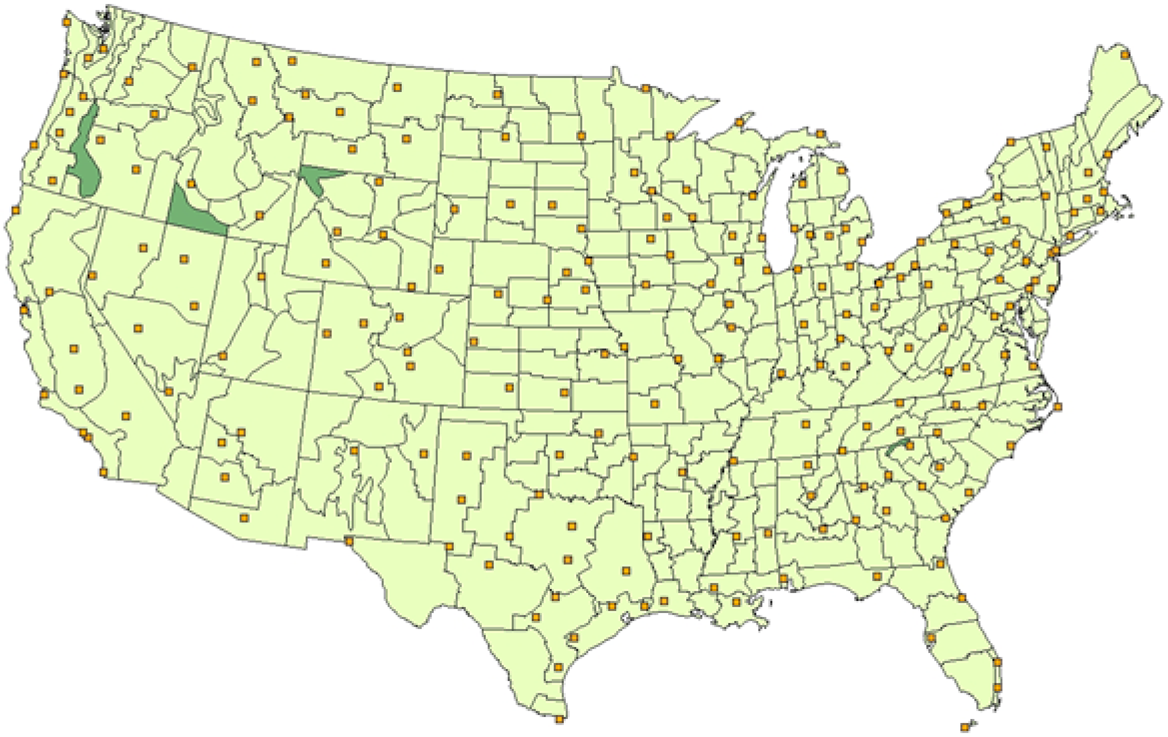

Figure 13. Map of US climate divisions (polygons) and weather stations contributing to the NSRDB solar radiation database (square points). Five climate divisions in dark green fill were excluded from spatial analysis after rectifying with county boundaries (Southwest Highlands, ID; Northern Cascades, OR and High Plateau, OR (shown as a single polygon), Mountain, SC; and Yellowstone Drainage, WY).

Table 1 contains the complete list of climate and related variables I attributed to monthly climate division records for each of the retained 339 climate divisions for the study period. The combined division code and month (DIVMONTH) is the basic spatial and temporal unit of observation for this study and the key value linking birth data and climate variables.

Table 1. Climate variables created for analysis from NCDC and NSRDB data.

Source	**Field Name**	**Description**
NCDC TD-9640	StateCode	Climate Division State Code
NCDC TD-9640	Division	Climate Division SubCode
Derived	DIVCODE	Combined State and Division SubCode
NCDC TD-9640	YearMonth	Year - Month of Calculated Conception
Derived	DIVMONTH	DIVCODE combined with Year Month
Derived	SEASON	Season of Conception (Dec – Feb: Winter; March – May (Spring); Jun – Aug (Summer); Sep – Nov: Fall)
Calculated	DAYLENGTH	Number of hours of sunlight per day at midpoint of YearMonth
NCDC TD-9640	PCP	Precipitation monthly mean in inches to 100ths
NCDC CLIM85	APRC	Average precipitation in inches for month for 1971–2000 period
Calculated	ZPCP	Z-value of PCP relative to APCP using standard deviation for APCP from Climate Normals table.
NCDC TD-9640	TMP	Temperature monthly mean in degrees F
NCDC TD-9640	ATMP	Temperature monthly mean in degrees F averaged 1971 to 200 period
Calculated	ZTMP	Standardized Z-value of TMP relative to ATMP using standard deviation for ATMP from Climate Normals
NCDC TD-9640	PDSI	Palmer Drought Severity Index (unitless)
NCDC TD-9640	PHDI	Palmer Hydrological Drought Index (unitless)
NCDC TD-9640	ZNDX	Palmer Z Index (z-value))
NCDC TD-9640	PMDI	Modified Drought Severity Index (unitless)
NCDC TD-9640	CDD	Cooling degree days
NCDC CLIM85	ACDD	Average Cooling Days for Month for 1971 to 2000 Period
NCDC TD-9640	HDD	Heating Days for Month
NCDC CLIM85	AHDD	Average Heating Days for Month for 1971 to 2000 Period
NSRDB	AVGLO	Average daily total solar radiation for the Global Element in atmospheric pressure in millibars (Wh/m2)
NSRDB	AVDIR	Average daily total solar radiation for the Direct Element in Wh/m2
NSRDB	AVDIF	Average daily total solar radiation for the Diffuse Element in Wh/m2
NSRDB	TOT	Average Total Sky Cover in 10ths
NSRDB	OPQ	Average Opaque Sky Cover in 10ths
NSRDB	TAU	Aerosol Optical Depth (unitless)
*	B_*x*	Value for each of the above climate fields in the preceding month (e.g, B_TMP is average divisional temperature in March 1978 for TMP value of April 1978)
*	A_*x*	Value of each of the above climate fields in the following month.

Birth Data

NCHS Natality Database

In the US, issuance of the birth certificate is a function of states. Birth or "natality" data for the US is collected from state agencies and distributed to the public by the National Center for Health Statistics (NCHS). NCHS issues a standard birth certificate form for use by states, but each may use their own. Data are distributed annually by the NCHS with an approximately three-year processing time. The quality and scale of the data has improved significantly since the early 1960s when the US Department of Vital Statistics began collecting and tabulating individual births from state data. Initial year datasets consisted of 50 percent samples from each state but almost all states reported 100 percent samples by 1980 and all states by 1985. Based on individual state reporting requirements, many fields are also missing data in early datasets or report according to differing definitions (e.g. "race of child"). Most significantly for this study, geographic data are not included in later birth datasets due to confidentiality requirements. Specifically, only natality public-use microdata files prior to 1989 contain all counties and exact dates (year, month, and day) of birth, while files for data years 1989 to 2004 contain geographic identifiers of counties and cities only with a population of 100,000 or greater, and in all records during this period only the year and month of birth is recorded. From 1989 to 1993, the 1980 census is used to identify counties below 100,000 population, while the 1990 census is used to identify these counties from 1994 through 2004. In counties with lower populations, only the state of residence is recorded. Because of increasingly stringent health information disclosure regulations, no geographic identifiers — state, county or city — are included in the public use data beginning in 2005. In 1994, for example, only 458 counties are thus identified with the county of residence, accounting for adjustments based on the 1990 census (Figure 14). Some counties identified in the 1989–1993 county of residence data are not identified after 1993 because their population dropped below 100,000 in the 1990 census.

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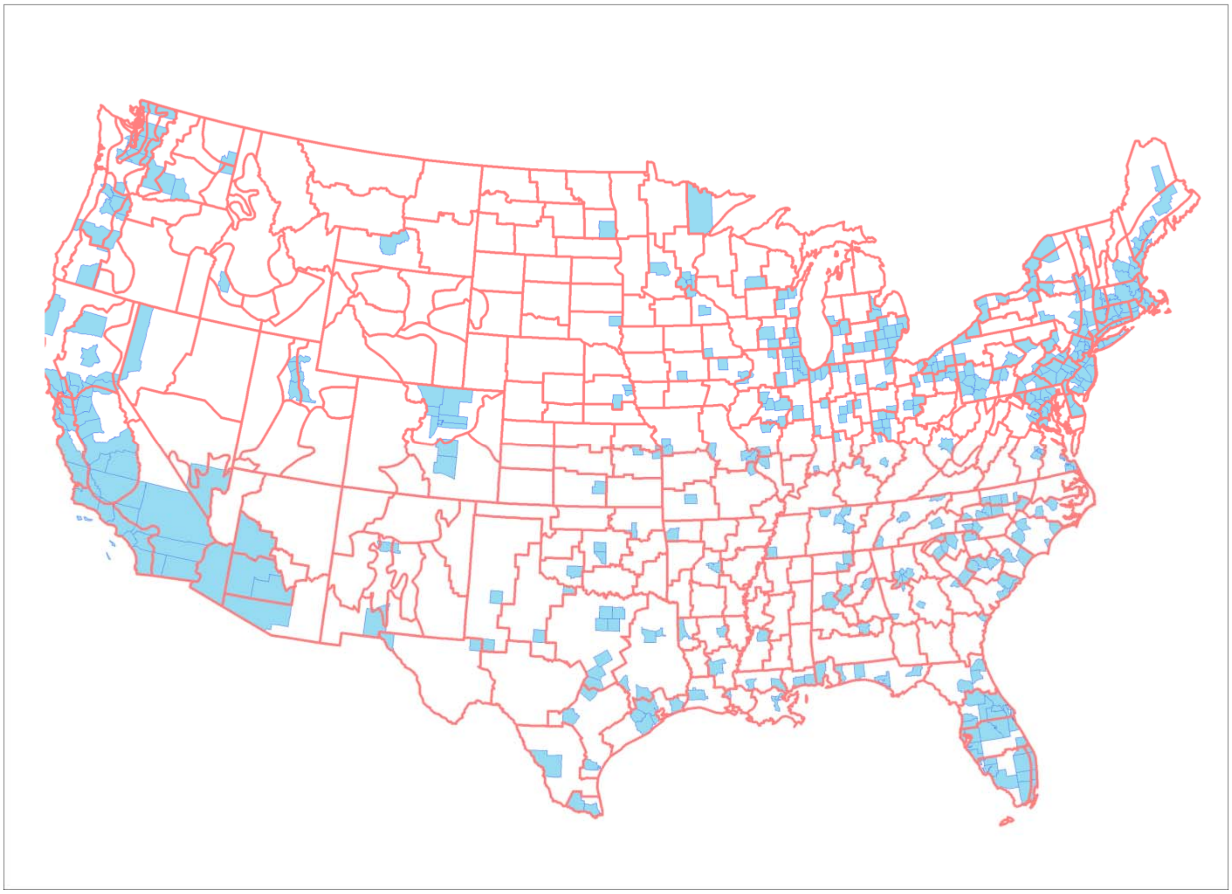

Figure 14. Map of counties for which birth data are not hidden in NCHS public use microfiles for 1994–2002.

Major revisions to the standard birth certificate occurred in 1978, 1989, and 2003. Prior to 1979, many states did not report gestation length on birth certificates, so this year was used as the starting year for analysis. Births registered from 1979 to 1988 are the baseline study period for geographic analysis since they can all be identified by county of residence and assigned to the geographically contiguous set of climate division for the continental US (excluding the five climate divisions I noted previously).

The geographically complete dataset prior to 1989 can be subjected to geographically weighted regression and other spatial data exploration. A major revision to the standard birth certificate in 1989 makes this year a convenient demarcation for study data. Another significant revision occurred in 2003, introducing additional data comparison issues over the study period, so I used

2002 as the end year of my analysis. To construct time series analyses over the entire 1979–2002 study period, I identified 403 counties for which geographic information is available for each year in the study period (Appendix 2).

The 1979–1988 NCHS birth data therefore serves as basis of the geographic study area dataset and the 1979–2002 NCHS birth data for the 403 largest US counties as the time series dataset. Data from 1989 to 2002 are used for a focused analysis of climate change effects, since the 1989 changes in the standard certificate required federal reporting of Hispanic origin. Geographic analysis of time series data over the entire study period and data from 1989 and later is limited to categorization by broad regional designations such as census division and latitude.

To compile natality data, electronic copies of national natality sets, “public-use microfiles,” for the study period were downloaded from the Inter-University Consortium for Political and Social Research (Institute for Social Research, University of Michigan (ICPSR)), which NCHS designates as the repository for public distribution of these files (NCHS 1981–2005). These files were downloaded in comma-separated value format and imported to a Microsoft SQL Server 2005 Database. Record counts in the database were compared to the ICPSR manifests to ensure all records were imported successfully.

For the 1979 to 2002 study period, the database does not represent a 100-percent record of live births. In 1979, the NCHS used 50 percent stratified random samples for Arizona, Arkansas, California, Georgia, New Mexico, South Carolina, South Dakota and District of Columbia; by 1985 NCHS recorded a 100-percentsample for all states and the District of Columbia. Based on the sample count, the 1979–1988 birth data represents 94.6 percent of all births recorded in the US during this period. Approximately 67 percent of all 50-percent-sampled locations in this period are in California; 63 percent of the records recorded from California during the study period are from a 50 percent sample of births in that state. For analysis using mapping and analysis of sex ratio by division, I did not make any adjustments to the data to account for this sample. However, where the weighting of the location of births was a factor in the analysis, I used the recordweight field of the natality dataset to double total births values in counties where 50 percent sampling was used. This weighting did not affect sex ratio calculations for these units of observation, but might, for example, change the representation of where the mean latitude of total births occurred by season.

The natality dataset county of residence field was selected as the geographic field of interest, since the county of birth occurrence might be a hospital or other location different from the county of residence, the most likely geographic site of conception and early gestation. For pre-1982 records, the county of residence is a unique NCHS county code; after that period, FIPS codes are used. I developed a crosstab table and rectified all county of residence codes to a consistent code across all study years. In addition, this crosstab table addresses inconsistent county-of-resident reporting across the study period. Cibola County, New Mexico was formed in 1981 from Valencia County; all study period births are aggregated to Valencia. Bronx, Richmond, Kings, and Queens boroughs are listed separately from 1985, but are aggregated to New York County to match pre-1985 records. Poquoson City, VA was independent as of 1985 but aggregated to York County across the study period. Similarly, Manassas City, VA and Manassas Park, VA were independent in 1985 but were aggregated to Prince William County. These and other rectifications to achieve a spatially consistent database throughout the study period are summarized in Appendix 3.

Individual birth records record a number of attributes that may influence SRB in addition to hypothesized climate conditions. These include the biological factors of livebirth order, plurality, and maternal age. Income, housing status, and other traditional socioeconomic indicators are not present in the record, but researchers have inferred these from education of mother, marital status, number of prenatal visits, and birthweight. While these attributes may be preserved in a logistic regression model, they are lost when aggregated to the climate division units used in this study. Race and origin attributes are recorded for each birth, however, and these may serve as proxies for socioeconomic status on a broad level. As cited in the literature review, SRB is consistently lower for births to African American mothers and those of Hispanic origin (Mathews and Hamilton 2005). Because of these differences, geographic distribution of births to African Americans and persons with Hispanic origin must be considered in this analysis. All births to mothers identified as black in natality data are only 15.8 percent of the total for this period, and many climate divisions report no births for this population for 1979–1988 births (see, for example, a map of births to black mothers calculated to be conceived in the summer months of the study period in Figure 15).

In addition to not being geographically contiguous, the set of climate divisions recording black births exclude many divisions that have extreme weather values, notably those recording the cold winters of the Midwest and Rocky Mountain states. In addition, the density of concentrations differs from other populations. Most of the African American population lives in the Southeast (54 percent), while 19 percent live in the Northeast; 18 percent in the Midwest, and 10 percent in the West. Approximately 79 percent of African Americans live in urban areas, further complicating the comparison among divisions because urban and rural environments may present different climate regimes, such as the urban heat island effect.

A further complication in attempting to control for racial distinctions is which field to use for classifying race: race of mother, race of father, or race of child. In the latter case, this value is based on the response of the mother. Since 1989 and the revision of the standard certificate, the NCHS uses the race of the mother for various birth tabulations. One reason cited by NCHS for this change is the increase in interracial marriage, which increased from 2.0 percent in 1977 to 5.3 percent in 1998. There has also been a significant increase in the number of records in which the race of the father is not stated (from 11 to 14 percent over the same period). Because of the large percentage of records which are missing any data about the father, I use race, age and education of the mother to define characteristics of the parents for the entire study period. I do not consider interracial marriage as a factor in my analysis because of missing data and because Marcus et al. 1998 did not find this factor to be significant in their examination of the change in US sex ratio between 1969–1995.

Hispanic births are a particularly confounding factor because of state inconsistencies in reporting during the study period. Ethnicity was not provided in the NCHS database until 1979, which partly determined the beginning year for the first study period. In the 1979–1988 data, 43 percent of the birth records report the mother origin field as nonclassified. About eight percent of total births are classified in one of the five Hispanic categories (Mexican, the largest, followed by Puerto Rico, Cuban, Central or South American, or Other or Unknown Spanish).

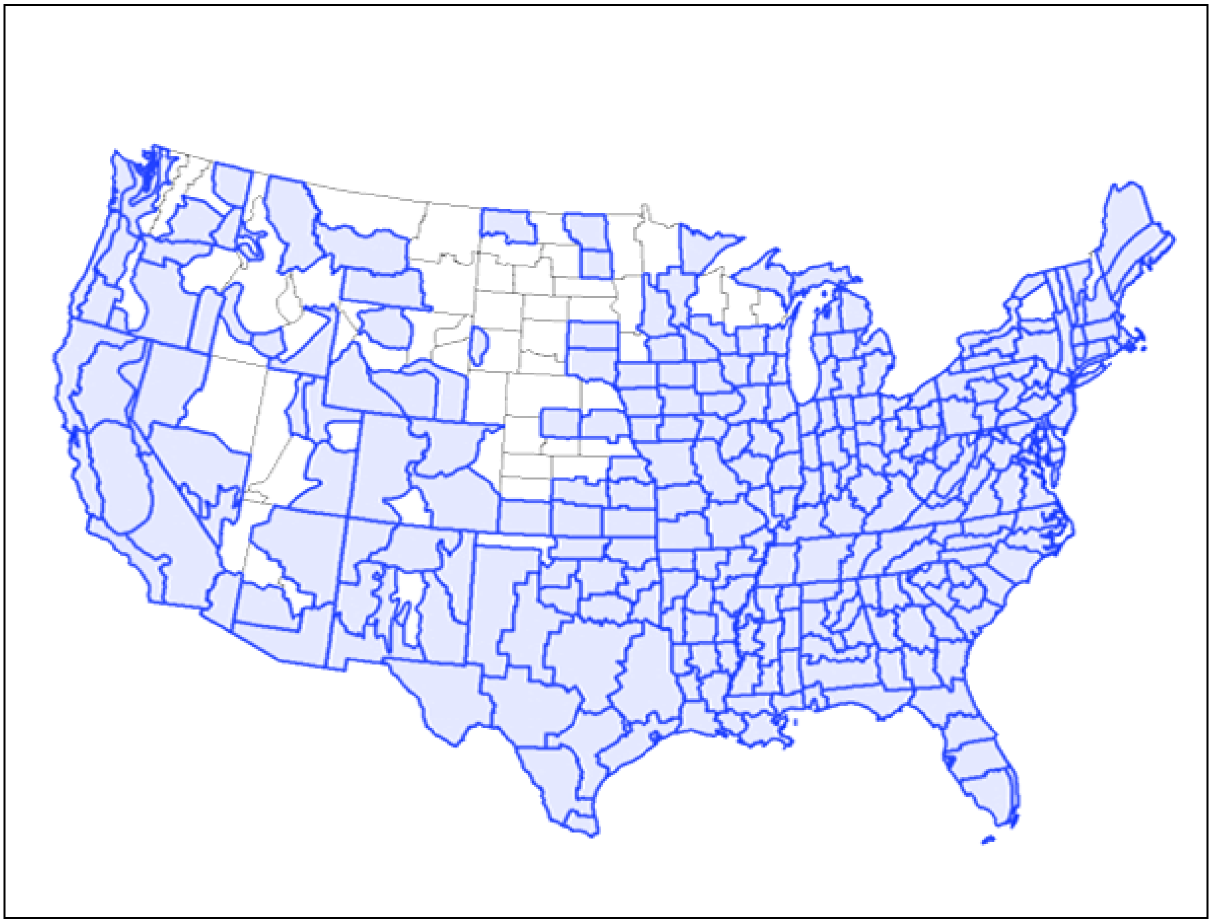

Figure 15. Map of US climate divisions in which births are recorded to black mothers for estimated summer conceptions in 1979–1988 NCHS data (gray fills and blue borders have records).

Because of the inconsistency of this reporting, Branum et al. (2009) excluded from records prior to 1989 consideration a study of the independent influence of Hispanic births on US SRB. However, for the geographic study, I classified births that did not have one of these five Hispanic origin codes as "non-Hispanic" even if the origin code was missing. I made this coding decision because the exclusion of over 40 percent of records would seriously bias the geographic analysis to states which reported Hispanic origin. Further, ethnic origin reporting states are those in which Hispanic populations are concentrated. In 1980, 22 states representing an estimated 90 percent of all births of Hispanic origin reported this information; by 1989 all but three states reported Hispanic origin (Louisiana, New Hampshire, and Oklahoma). In 1990 only New Hampshire and Oklahoma did not collect information on Hispanic origin, while in 1991 and 1992 New Hampshire was the only state that did not ask for this information. There has been full reporting of Hispanic origin from all States and the District of Columbia since 1993. The total percentage of births in the 1979–1988 data classified as Hispanic when missing values are coded as non-Hispanic is eight percent, very close to the reported total population of Hispanics in the US Census, ranging from 6.4 percent in 1980 to about 9 percent in 1990. Therefore, missing ethnic origin is a potential bias to the geographic study analysis but not sufficient to dismiss the spatial and temporal patterns I report. To fully assess this factor, I also consider climate effects on a subset of the time series database that begins in 1989, similar to the method used by Branum et al. (2009).

Month of Conception

Conception date, a critical value for this study, is not explicitly coded in the NCHS records since it is usually a matter of guesswork and estimation. Calculating a month of conception from available data is complicated by several factors. NCHS records based on the standard birth certificate include the first day of the last menstrual period (LMP) and the physician's clinical estimate of gestation length in weeks (GW). Although the gestation period in animals is understood to be the time between conception and birth, the standard calculation of human gestational age is the interval between the LMP and date of delivery. A woman is usually able to get pregnant for about 5 days each month, when ovulation occurs. On average, ovulation occurs 12 to 16 days before the menstrual period begins. Because sperm can live for 3 to 5 days in a woman's reproductive tract, it is possible to become pregnant if intercourse occurs several days before ovulation. In general, conception is estimated to occur at the midpoint of a typical 28-day menstrual cycle, so the gestational age value in NCHS records overestimates the length of pregnancy by an average of two weeks. For LMPs that occur in the latter half of a calendar month, the month of the LMP may be prior to the month of conception.

The accuracy and completeness of the reported gestation date is also an issue. The LMP has been required at the national level only since 1981, while the clinical estimate of gestation has been required since 1989. The physician's estimate of gestation weeks and the LMP should theoretically be the same, but a number of studies have documented the scale of differences between these two values in the NCHS data (e.g., Dietz et al. 2007). These values are subject to error in obstetrician estimate or mother's recollection, irregular menstrual periods, variations in fertile periods and other medical conditions. To aid in research of preterm rates and other birth health statistics, the NCHS has imputed the gestation weeks value for most records where it is missing or apparently inaccurate, using the LMP and cross indicators such as birthweight. In the 1979–1988 geographic dataset, approximately 5.3 million records are missing complete LMP dates (month-day-year), although many of these contain the month and year of this event.

Although missing in about 2.7 million records in the 1979–1988 dataset, the gestation weeks field appears to be a better value to use than LMP in estimating conception during this period since it has the fewer missing values and also reflects NCHS adjustments to implausible LMP values. Further, natality records during this period contain month-day-year birthdates, so the month of conception can be calculated more precisely than after 1988 when only the month and year of birth is recorded to preserve confidentiality.

The typical gestation period is 40 weeks, which is also the modal value of the gestation weeks field both the 1979–1988 geographic dataset and the 1979 to 2002 data for large counties. A range of 37 to 41 weeks is considered normal or "term"; the NCHS gestation weeks field allows values ranging from 17 to 52 weeks. Although the accuracy and completeness of the gestation information has flaws, it allows for a much better estimate of seasonal conditions at the time of conception than use of a standard nine-month backdate from time of delivery (e.g., Seiver 1985). As Figure 16 shows, the month of conception could vary one or more months from this nine-month standard for a substantial percentage of births.

Because the gestation weeks field has the fewest missing values and an accurate day of birth date, I selected it as the basis of calculating month of conception for the 1978–1988 dataset, the basis of most of the spatial analysis in this study. I converted gestation weeks to gestation days and subtracted this number from the day of birth :

$$conceptiondate = birthdate - (gestation\ weeks * 7)$$

The month and year in which the conception date fall is the conception month/year and was used to construct the division/month/year (DIVMONTH) field for joining to climate variables. Approximately nine percent of the birth records of the geographic dataset occurring in the 339 climate divisions of the continental US could not be assigned a DIVMONTH value using this method.

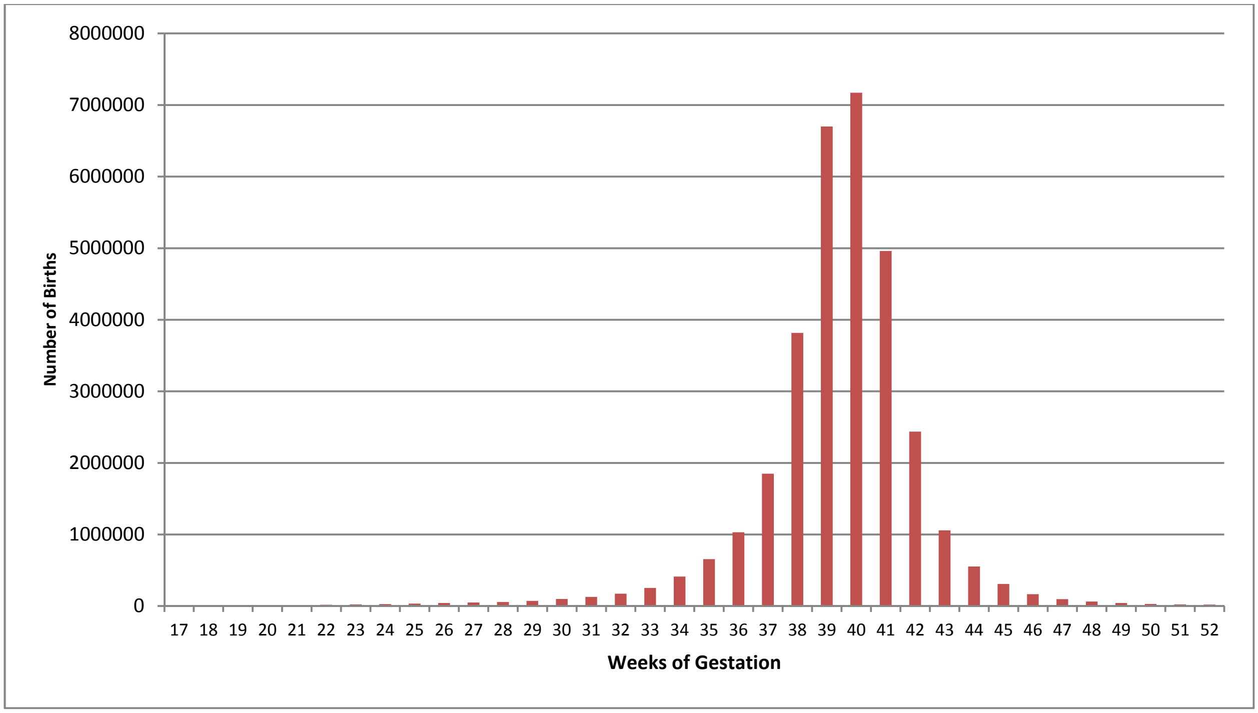

Figure 16. Total births by weeks of gestation, 1979–1988 NCHS data. Values on the X axis represent the range of allowed values in the NCHS gestation weeks field.

Construction of Research Databases

The total number of NCHS records for the geographic dataset (1979 to 1988) is 35,142,111, without adjusting for 50 percent sampling from 1979–1984 in some states. Excluding Alaska and Hawaii and births to Island territories (341,740), the geographic dataset has 31,698,168 birth records for which a conception month can be assigned using the gestation weeks (GW) method. Using the GW method on a birthset beginning in January 1979 and ending in December 1988 produces conception dates as early as January 1978 (significantly postterm) and as late as August 1988 (significantly preterm). Because preterm births are significantly male biased and postterm births are significantly female biased, monthly aggregations of sex ratio are similarly skewed at the beginning and ending of the study period. For example, conception dates estimated as April 1988 or later include only preterm births registered in 1988. No offsetting normal term births from early 1989 are included since they lack full geographic specificity. SRB for conception months April 1988 to August 1988 are indeed significantly higher than for any other month in the study database, except for August 1988, which had only 300 births. Similarly, postterm births are overrepresented in the early months of 1978. To avoid confounding climate effects with postterm and preterm bias effects, analyses of monthly aggregated time periods in the geographic dataset use births estimated to have been conceived between January 1979 and December 1987. For seasonal aggregations, I use the period December 1978 to November 1987, a one-month backshift.

Because of the lack of geographic specificity in births in 1989 and later, climate divisions can only be assigned to 403 counties for the period 1979–2002 in public use NCHS records. I call this the *time series database.* It uses LMP to calculate the month of conception since day of birth is omitted after 1988 and cannot be used to calculate GW. The LMP method produces 62,850,545 records that can be assigned a conception month and division code (excluding Alaska and Hawaii). This includes the 50 percent recordweight records that I duplicated in the 1979–1984 period to avoid biases in geographic aggregations**.** The total number of records, 50 percent recordweight records, and estimated year of conception for the original NCHS dataset and in both the geographic and time series research databases are shown in Table 2.

Table 2. Record counts for total NCHS database (All Records), Geographic Database (US Counties Excluding AK and HI), and Time Series Database (US large counties).

Year	All Records Registered Year of Birth	US Counties (Excluding AK and HI) Estimated Conception Year (GW)	US Largest Counties (n=403) Estimated Conception Year (LMP)
1978(100%wgt)	-	1,574,138	1,221,117
1978(50%wgt)		177,652	166,043
1979 (100 %wgt)	2,869,047	2,303,870	1,786,659
1979 (50%wgt)	315,374	230,845	230,080
1980 (100%wgt)	3,002,621	2,757,756	1,873,633
1980(50%wgt)	307,680	274,616	239,252
1981(100%wgt)	3,002,593	2,856,377	1,929,146
1981(50%wgt)	316,461	293,220	247,456
1982(100%wgt)	3,068,169	2,827,424	1,923,227
1982(50%wgt)	308,644	290,970	250,092
1983(100%wgt)	3,032,945	2,811,036	1,929,386
1983(50%wgt)	304,938	293,462	254,203
1984(100%wgt)	3,048,174	3,363,774	2,410,727
1984(50%wgt)	312,697	73,392	62,459
1985	3,765,064	3,522,232	2,561,724
1986	3,760,695	3,529,267	2,594,275
1987	3,813,216	3,625,118	2,679,817
1988	3,913,793	893,019	2,777,842[1]
50%wgt * 2			**1,449,585**
Total Records 1979–1988	**35,142,111**	**31,698,168**	**26,586,723**
1989	4,045,693	N/A	2,884,442
1990	4,162,917	N/A	2,861,356
1991	4,115,342	N/A	2,820,591
1992	4,069,428	N/A	2,796,904
1993	4,004,523	N/A	2,749,824
1994	3,956,925	N/A	2,702,109
1995	3,903,012	N/A	2,619,851
1996	3,894,874	N/A	2,642,953
1997	3,884,329	N/A	2,654,868
1998	3,945,192	N/A	2,665,126
1999	3,963,465	N/A	2,715,329
2000	4,063,823	N/A	2,750,842
2001	4,031,531	N/A	2,728,177
2002	4,027,376	N/A	671,450
Total Records 1989–2002	**56,068,430**	N/A	**36,263,822**
Total Records 1979–2002	**91,210,541**	**31,698,168**	**62,850,545**

[1] Includes births registered in 1989

All attributes and records in the master NCHS database (*n*=91,210,541) were retained in Microsoft SQL Server 2005 (SQL Server) and additional fields calculated to populate the two research databases and subsets exported to SAS Software v.9.2 for x_64 (SAS Software) for statistical analysis. A county Federal Information Processing System (FIPS) code was calculated for each birth record, requiring rectification of the NCHS county code system used in the 1979–1981 period of the database and aggregation where counties have merged during the study period, as described in Appendix 3.

The County FIPS field served as the key for joins to a master database of county level socioeconomic values for the study period compiled from ICPSR-distributed databases from original data collected by the US Census Bureau, US Department of Labor, the Bureau of Economic Analysis, and a number of other agencies and distributed as the City and County Data Book. These provide socioeconomic context in addition to parental maternal education and marital status from the birth record, which I use as proxy for individual economic condition. After initial exploration for significance and multicollinearity in logistic regression, I retained socioeconomic variables for infant mortality rate (IMR), per capita income (PCI), and percent below poverty level (POVLev). I also added monthly Consumer Confidence Index values (The Conference Board 2011) to each record to determine influence of time varying economic pressures.

I also included a number of county level classifications of climate, such as the Koppen Climate Classification and the Building America Climate Region, that are included as environmental characteristics in the ICPSR County Characteristics 2000–2007 database (ICPSR 2007). Monthly variables for El Nino-Southern Oscillation (ENSO) were also added to see if this climate signal explained variation in sex ratio at conception.

The GW (for the geographic database) or LMP (for the time series database) calculation for each birth was concatenated to the assigned climate division code based on the rectified county FIPS code to create the DIVMONTH key field for matching to the master climate table of monthly values, which consisted of 97,632 records encompassing the calculated dates of conception during the study period (339 climate divisions * 12 months * 24 years). Along with the contextual demographic and economic variables and monthly climate factors assigned to each birth record from the joined climate and county databases, each research dataset record contained at least the following individual characteristics:

1. Recordweight. 1979–1984 records representing 50 percent samples.
2. Maternal education. Number of years converted to class variables.
3. Maternal age. Number of years converted to class variables.
4. Maternal race. NCHS codes for White, Black, and Other.
5. Birth order. Live birth order converted to class variables.
6. Gestation weeks. Number of weeks converted to class variables.
7. Plurality. Number of live births in single delivery converted to class variables.
8. Hispanic origin. Mother's origin converted to yes/no class variable.
9. Marital status. NCHS codes for married and unmarried mothers.

Statistical Analysis Methods

General Approach and Final Model Selection

The primary analytical challenge of the research question is a model that explains or predicts the influence of general ecologic or environmental factors in the geographic area where the birth occurred, while controlling for the individual factors of the parents that have been shown to influence the SRB, such as birth order and plurality of the child and marital status of the mother. To develop a final model to answer these questions, I used both logistic and linear regression models for this research problem, applying different methods for the geographic study of 1979–1988 birth data and for time series data of US large counties from 1979–2002.

The NCHS data is very complete, with an estimated 99 percent of all births occurring in the US in 2002, including 99.5 percent of white births and 98.6 percent of other births (NCHS 2002). In my exploratory analysis, some analysis is descriptive and made based by viewing choropleth maps and bar or line charts. Chart graphics are prepared in SAS or Microsoft Excel and sometimes include confidence intervals for sex ratios, which are given as the male proportion of the sample population. Confidence intervals of the male proportion statistic are calculated in Excel using the Wilson score formula based on the recommendations of Brown et al. (2001). This formula yielded the same results as other methods tested (e.g., Agresti and Coull 1998), and did not differ in results from the normal approximation formula due to the large size of n (from 20 to 60 million) in the subpopulation samples I compare. The normal approximation method assumes that in large samples the binomial distribution will approximate a normal distribution and a confidence interval can be calculated as:

$$\pm z * \sqrt{\frac{\hat{p} * (1 - \hat{p})}{n}}$$

where $z = 1.96$ – for a 95 percent confidence level, $\hat{p}$ is the sex ratio as male proportion and n is the total number of births in the sample. The Wilson score improvement brings the actual coverage probability closer to the nominal value, as

$$\left(\hat{p} + z^2_{\alpha/2}/2n \pm z_{\alpha/2}\sqrt{\left(\hat{p}(1-\hat{p}) + z^2_{\alpha/2}/4n\right)/n}\;\right) \Big/ \left(1 + z^2_{\alpha/2}/n\right)$$

where $\hat{p}$ again is binomial proportion and $z_{\alpha/2}$ is the $100(1-\alpha/2)$th percentile of the standard normal distribution. For a 95 percent confidence level interval, this may be calculated in Microsoft Excel as:

```
((1.96*1.96)/(2*n)+[or – for lower limit]1.96)*(SQRT((p*(1-p)+(1.96*1.96))/(4*n)/(1+(1.96*1.96)/n)))
```

For several comparisons I use tests of association for categorical variables typical for sex ratio research: chi square goodness of fit and chi square for linear trend, both suitable for large sample populations. G-tests are also frequently used in more recent studies, but I use chi-square for familiarity and comparison to older studies. Unless otherwise specified, chi-square goodness of fit values are the Pearson Chi-Square method and Mantel-Haenszel chi-square test of linear trend as implemented in SAS.

Although linear regression using the male proportion as the dependent variable is used in some sex ratio studies, proportions are not recommended for such analysis. The sex ratio at birth value for a climate division month does not have any information about the size of the sample in that observation — it is not a true measurement variable. Linear regression also assumes that the dependent variable has a Guassian distribution, rather than the binomial distribution of the male proportion. Due to these limitations, results from such models are suspect, but I use them here because available spatial analysis techniques are not well developed for logistic regression and because sample sizes were often large enough to assume normal distributions. I use male proportion as the dependent variable for ordinary least squares regression (OLS) and geographically weighted regression (GWR) to choose likely climate variables of influence and to assess the significance of spatially varying patterns of these factors.

The research for this study was primarily an iterative process of exploring spatial and temporal patterns to arrive at a well specified global logistic regression model and an understanding of the relationship of SRB to hypothesized climate variables. Logistic regression has a number of desirable characteristics for sex ratio studies. As typically applied in sex ratio studies, logistic regression uses the logit of the probability of a male birth. Normality assumption is not needed for logistic regression. Because the underlying error of the sex ratio is presumed to be binomial, this error is incorporated in the modeling process. Logistic regression modeling avoids the need to transform data to meet distribution requirements for parametric tests; it also has very good power compared to many nonparametric tests. SRB researchers using logistic regression can thus avoid *ad hoc* transformations required by methods that must have normal distributions, or nonparametric tests that lack power. In their survey of statistical methods used for sex ratio research, Wilson and Hardy (2002) assert that logistic regression modeling is a superior form of analysis for sex ratio statistics, although the majority of studies they reviewed use nonparametric or classical parameter models.

The independent variables of logistic regression can be a mixture of continuous and categorical variables, a virtue of generalized linear models in which simultaneous testing of several interacting factors and covariates can occur within a single model. The generalized linear model in this study combines individual case variables, such as race and birth order, with climate variables that are hypothesized to affect the hormonal environment. Each record in this model assesses the sex of the newborn in the context of a proxy socioeconomic and biological assessment of the mother and several parameters of the local climate which she is likely to have experienced prior to conception and during gestation, presuming this occurred in the same county as the NCHS recorded county of residence.

Because of its facility with large datasets, SAS was used to conduct all nonspatial statistical analysis, except where noted. The binary logistic regression method is used to test the strength of the association between the dichotomous dependent variable *Y* — the sex of the child — and selected climate variables, while controlling for the effects of family factor confounding variables. Using the logit model, this software uses standard nonlinear transformation of an ordinary linear regression to allow probabilities to fall between 0 and 1. For multiple independent variables, the logit equation can be given as

$$p(Y) = \frac{Exp(\alpha + \beta_1 x_1 + \beta_2 x_2 \ldots + \beta_i x_i)}{1 + Exp(\alpha + \beta_1 x_1 + \beta_2 x_2 \ldots + \beta_i x_i)}$$

Where, *p*(*Y*) is the probability (*p*) that individual case *i* will be a member of *Y*, such that *p*(*Y*)=1 (i.e., a male birth), *Exp* is the exponential function raising the Euler number to the value within the parenthesis, α is the coefficient of the constant (i.e., the intercept, or the value of the independent variable *x* when *Y* is 0), and *β* is the coefficient of the independent variable.

Spatial and Temporal Analysis

Logistic regression poses problems for analysis of spatial dependence. One method to counteract spatial dependence is to develop sampling schemes to expand distance intervals, but this method results in the loss of potentially important data in omitted samples. Also, since logistic regression models do not require normalized distributions, many diagnostic tests developed to assess spatially dependent error in residuals for linear regression methods are not applicable to logistic regression. Therefore, I used linear regression with aggregated sex ratio at the division level for some of the exploratory spatial and temporal analysis.

As mentioned above, linear regression is not recommended for sex ratio proportions because this value is really a dichotomous variable that, in theory, conforms to the binominal distribution and is thus constrained by 0 and 1. Linear regression models could potentially predict outcomes beyond these constraints because it assumes a linear distribution, where the shape of the theoretical binomial distribution is sinuous, not the linear shape that OLS regression assumes. Further, since proportion is not a measurement value, as is also assumed by the linear regression model, small samples have equal weight to large ones when expressed as proportions: e.g., the male proportion of Morgan County, Tennessee births has equal weight to the same variable for Los Angeles County, California in this analysis. However, linear regression can be used for proportion analysis provided that population samples meet certain requirements and distributions are adjusted for normality (Wilson and Hardy 2002). As Zar (1999) notes, binominal distributions resemble Guassian distributions in large sample populations. Distribution for the 1979–1988 division/month sex ratio (ALLSR), and for selected subpopulations of that study period are normally distributed according to SAS statistical tests for normality (Kolmogorov-Smirnov = <0.010, Cramer-von Mises = <0.005, Anderson-Darling <0.005) and display skewness values within a range of normal (Table 3) .

However, kurtosis values are excessively high (greater than 3) for ALLSR (Figure 17), WhiteSR and WHITESR first born singletons, and all display high peaks around the median and long tails. The sharpness of this curve and the length of its tails is a function of the tendency in any division with even a moderate number of births to group towards the mean sex ratio at birth.

As the sex ratio at birth literature shows, the consistent variation of interest occurs in the third or fourth decimal point value of male proportion values in large populations (e.g., 0.5124 vs. 0.5129). In the climate division/month dataset, outlier values are primarily those in division/months with low number of births. For example, a histogram of climate divisions showing male proportion for black births have spikes at 0.34 and 0.66, months in which a climate division only recorded 3 total births for this population (Figure 18).

These outliers probably overly influence results by biasing the estimates of standard errors. This distribution also results in a high number of failures of tests for heteroscedasticity on classic linear regression methods, as measured by the White test.

Table 3. Climate division/month-year distribution characteristics for all births and for selected subpopulations.

Variable	Std Dev	Median	Kurtosis	Skewness	Mean
All births (ALLSR)	4.1033653	51.26294	9.0446063	0.0398138	0.512641
Mother of child white (WHITESR)	4.4818801	51.359084	8.4276036	0.0029309	0.513648
Mother of child black (BLACKSR)	9.6391287	50.361446	2.8536727	-0.0628412	0.506639
WHITESR First born singletons	6.7861199	51.428571	5.0161204	-0.0983128	0.514157
BLACKSR first born singletons	10.709106	50	1.5053713	-0.0349897	0.508819

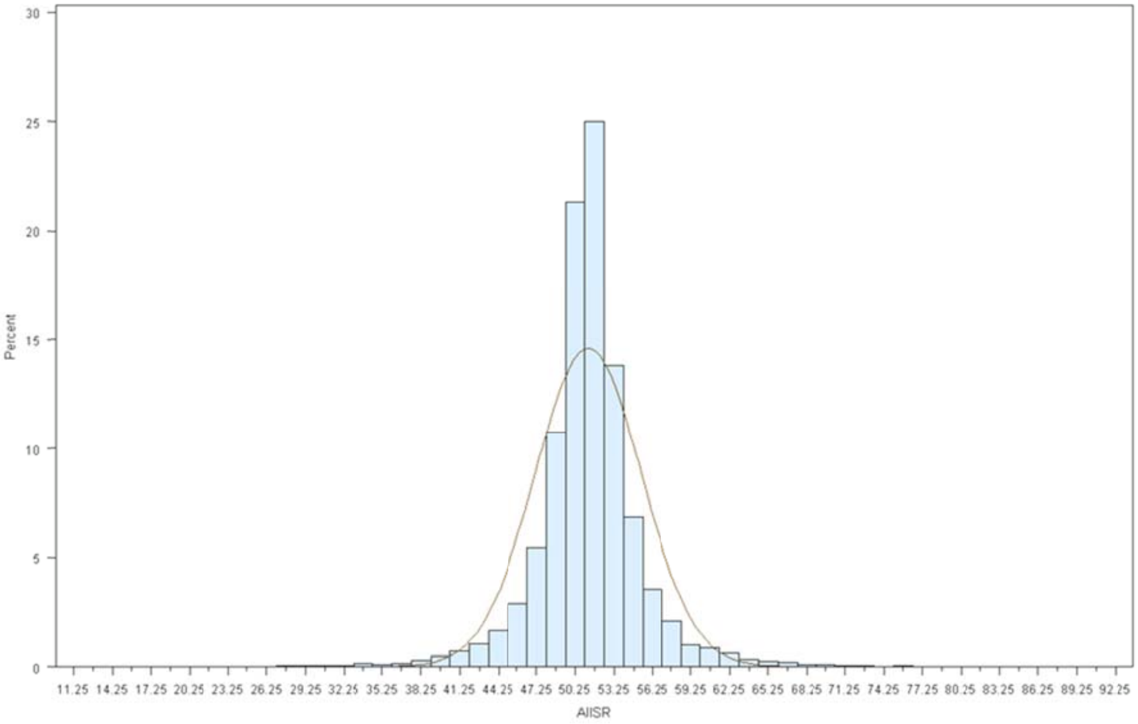

Figure 17. Histogram of climate division sex ratio values by month and year for all births in 1979–1988 dataset.

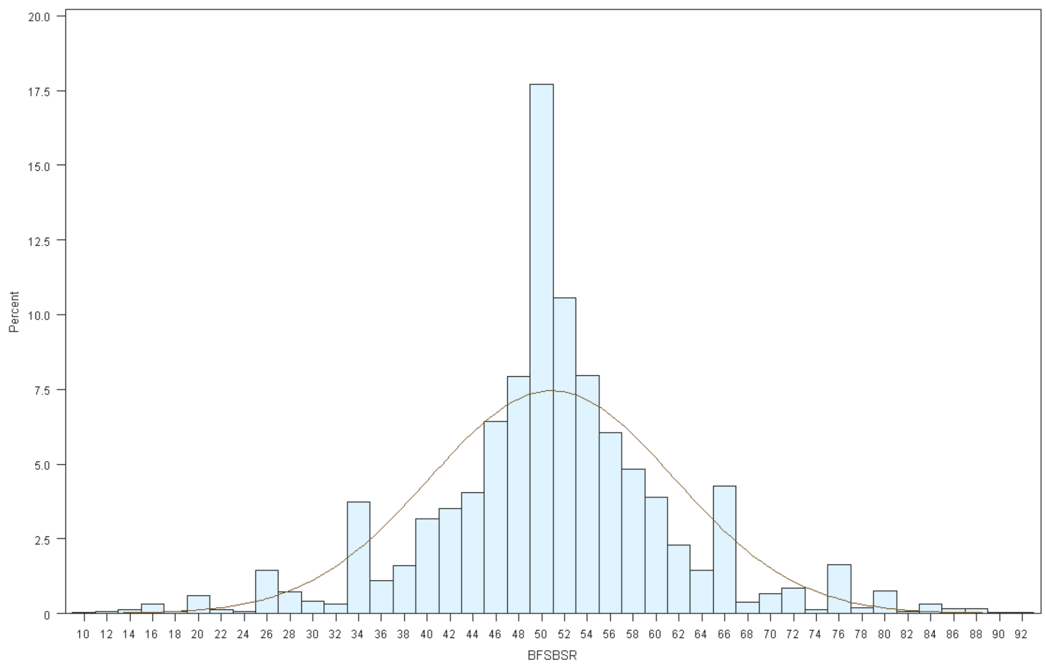

Figure 18. Histogram of sex ratio of first born single births to black mothers by climate division, 1979–1988 data.

To reduce but not eliminate the issues associated with use of SRB as a dependent variable and the excess influence of residuals in the climate division SRB dataset, I used weighting and aggregation methods available for each statistical tool. I judged the results to be sufficient for exploring spatial and temporal variation patterns. For exploration of space and time trends in SAS, I used a weighting method for linear regression called robust regression. This method was developed to detect outliers and to provide stable results in their presence. It provides a compromise between deleting observations without a compelling reason — the distribution of these outliers may be interesting — and retaining them even if they violate the assumptions of traditional linear regression methods. I use the method described by Huber (1973) and implemented in SAS as the Huber - M estimation. This is one of four SAS robust regression approaches and is the simplest approach computationally and theoretically; it is recommended for outlier distributions in the independent variable, which is appropriate for small population climate division months with small numbers of births. After computing standardized values for each residual, the Huber M estimator reduces those which exceed a selected standardized value

— I selected the default of three standard deviations. Using this model, I subjected each of the populations to regressions against the independent climate variables.

I use geographically weighted regression (GWR) to assess some of the patterns of this SRB heterogeneity and its relationship to the hypothesized independent variables. GWR is one of a number of local statistics models that assess the influence of independent variables within smaller geographic units of a study area in order to provide insight into processes that vary by spatial context. To reduce the impact of residuals from small climate division monthly total births values on the analysis, I aggregated all births by season within each climate division for the 1979–1988 geographic data, using averaged divisional values for each season over the entire study period as independent variables. I used the monthly assignment of seasons used by NOAA in their summaries of seasonal datasets: December–January–February=Winter; March–April–May=Spring; June–July–August=Summer; September–October–November = Fall). For this analysis, I used the GWR methodology developed by Fotheringham et al. (2002) as incorporated in ESRI ArcGIS 9.3.1 GIS software GWR extension. The local regression model provided is

$$y(u,v) = \beta_0(u,v) + \beta_1(u,v)x_1 + \varepsilon(u,v)$$

where y is the dependent variable, x_1 is the independent variable, β_0 and β_1 are the parameters to be estimated, ε is a random error term, assumed to be normally distributed, and u, v are the centroids of the climate division. The local regression models for the sex ratio values and selected climate variations each climate division are assessed using values in the nearby climate divisions according to an autoregressive spatial weighting algorithm. For each of these local models, parameter estimates and standard regression diagnostics such as R^2 are reported.

Using these same aggregated season values, I assessed climate values as independent variables in a linear regression model that diagnoses and corrects for spatial dependence. This OLS linear regression tool is provided by GeoDa (Anselin et al. 2006), developed by the Spatial Analysis Laboratory in the Department of Geography at the University of Illinois, Urbana-Champaign to test for significance where spatial dependence might be present. Spatial dependence diagnostics are based on spatial lag models (in which the dependent variable in a particular place is affected by independent variables in nearby places) or spatial error models (in which the error terms across spatial units are correlated). These tests include Moran's I (spatial error), LaGrange Multiplier (spatial error), LaGrange Multiplier (spatial lag), Robust LM (spatial error), and a portmanteau test (Robust LM + Lagrange Multiplier + Robust LM). If spatial dependence is detected, the model can be re-estimated using a maximum likelihood approach that corrects for spatial dependence. The spatial lag function in GeoDa requires a weight file, which I created using a threshold distance function using Euclidean Distance and the x and y centroids of the 339 divisions. I accepted the minimum threshold distance calculated by the program (approximately 310,000 meters). As comparison I also used contiguity weights (Queens Contiguity and Rooks Contiguity), each with 1 order of contiguity. These produced similar results, although the Euclidean Distance weight was slightly less likely to report spatial autocorrelation in the model.

I used both ArcGIS 9.3.1 and GeoDa for additional local and global spatial analysis. These methods include global spatial autocorrelation (Global Moran's I), high/low SRB value clustering (Getis-Ord General G), cluster and outlier analysis (Anselin's local Moran I), and hot spot analysis (Getis-Ord G_i^*). Global Moran's I provides an index and a z-score identifying the significance of clustering of high or low values or low/high or high/low values present in the entire dataset. Getis-Ord General G is also a global statistic but the z-score is positive when high or larger values are clustered and negative when low or smaller values are clustered. Anselin's local Moran I uses spatial weighting to detect local clusters of high/high, low/low, high/low or low/high values. Getis-Ord G_i^* identifies local hot spots in the context of neighboring values. A particularly useful visualization tool in this analysis was spatial empirical Bayes smoothing. This method creates a thematic map of climate division sex ratios calculated using total number of boys and total number of births, and then smoothing these rates based on sample size and rates of contiguous climate divisions.

Scan statistics as implemented in SatScan (Kulldorff 2010) were used to detect spatial or space-time clusters of high or low division/month/year sex ratio values. Significance is determined by a modeling simulation in which a spatial or temporal window is automatically resized to detect the clusters of units that exceed expected outcomes. The small sample size of many division/month/year units is not an issue in this autoregressive approach, as it is for OLS regression. I used the Bernoulli-based model with males as cases and females as controls to search for nonrandom patterns in space or time for each division and in each month over the 1979-1988 study period. The scan statistics exploration was useful in identifying Hispanic origin as a significant spatial variable.

For several analyses, I display seasonal or monthly birth rates, which are calculated using standard demographic methods to transform crude births into seasonal or monthly rates that account for variations in length of months and for leap years (see for example, Siegel and Swanson 2004). To calculate seasonal birth rates for the ten-year period 1979–1988, for example, use the formula

$$A_i = \frac{S_i}{D_i} \times 3653/4$$

where *i* is the season, *A* is the adjusted number of births, *S* is the total number of births in the month for a season, and *D* is the number of days in the season. The total number of days in the ten–year period is 3653, including 3 leap year days.

Finally, a number of time series analyses were conducted using SAS software procedures. The SAS PROC SPECTRA was conducted on monthly sex ratio and birth rate values over the 1979–2002 data period to look for periodicities or cyclical patterns in the data. The SAS Time Series Forecasting Tool was used to assess temporal stationarity, white noise in temporal patterns, and fit to candidate smoothing models that detect trending, serial autocorrelation and seasonal root patterns.

Limitations of the Study

The primary limitation of the study is incomplete birth data from the NCHS public use natality dataset. Data prior to 1979 was judged to be incomplete or inaccurate for comparison to later data. Inconsistent reporting by states for certain birth variables also complicated time series analysis, particularly identification of Hispanic origin prior to 1989. Incomplete information for fields specifying maternal education and paternal age and education, and other potentially influential individual factors of SRB are also a limitation to the study. Because paternal data is more often absent, the study biases parental effect towards that of the mother.

Confidentiality in the public use natality dataset also limits analysis of geographic extent for periods after 1988 to counties with populations over 100,000. The more geographically complete analysis for the period 1979–1988 is potentially biased by inconsistent state reporting that was partially rectified for births on the revised 1989 standard certificate. Analysis is also largely concentrated on non-Hispanic white mothers because of their wider geographic extent and majority proportion in the overall US population, although detailed study of other US populations might also provide insight into the relationship of climate and SRB.

Estimating the month of conception throughout the study period required use of the last menstrual period (LMP) field, although using the clinical estimation of gestation could have provided a more precise and complete estimate. The use of either the LMP or the clinical estimation of gestation to establish the month of conception is flawed because the actual month of conception could be later than the LMP or earlier than the beginning of gestation.

The assumption that climate variables in the county of residence represent conditions experienced by the mother at the time of conception and during gestation does not consider the possibility of parental migration during this period. The assignment of climate variables based on climate division aggregations over a monthly time period, which may level extreme conditions experience on the days surrounding conception. Further, climate division variables are sometimes aggregated over large geographic areas with diverse elevation and other factors that could vary significantly during a monthly period. Climate data is also temporally aggregated into seasonal units as well, further obscuring the direct relationship of climate on an individual birth. The research approach also does not account for the fact that climate is not experienced equally by all citizens of a geographic observation unit. Mothers in higher economic classes may be buffered from the more extreme effects of weather. Socioeconomic status is assessed in some analysis by maternal education, which is missing in a number of NCHS records.

Finally, the research approach operates without a clear understanding or consensus in the research about the proximate mechanisms of how or when human reproduction responds to changes in temperature, precipitation, daylight hours, or other climate variables considered in this study.

Organization of Results

With the construction of two major research datasets from a master database of 91,210,541 records and the selection of appropriate statistical methods, I now proceed to the analysis of SRB for various models. I present my results in two chapters. Chapter 4 analyzes 1979–1988 data, with particular emphasis on spatial patterns of SRB variation in relation to climate variables. This analysis serves to reduce the number of candidate climate and socioeconomic variables that influence SRB and provides a baseline against which to assess the decline in SRB that can be detected over the 1979–2002 period. Chapter 5 presents the results of my study of this decline and particularly focuses on the change in monthly and seasonal values of SRBs within broad latitudinal zones. Possible confounding effects of demographic change are also evaluated.

Chapter 4: The Geography of the US Sex Ratio at Birth, 1979–1988

Sex ratio research is a landscape full of mirages of significance. William H. James (1987) wrote of the particular melancholy that happens at the end of a day of research in which every possible variable seems to influence the sex ratio at birth. In the same vein, Bonde and Wilcox (2007) said that the sex ratio "is an endpoint particularly vulnerable both to false positive reports and fanciful interpretation." The peripatetic exploration described in this chapter produced many chimeric results, most of which I have spared the reader. However, this exploration detected regional and seasonal variation in the US SRB and associations with similar variation in fertility. Recognizing these relationships requires various methods to visualize and quantify in geographic terms and in the context of monthly, seasonal, annual and multi-year variation. A map of this cluttered route begins this chapter.

Seasonal variation of sex ratio at birth and fertility (birth rate). The aggregated monthly SRB and fertility during the early and late stages of the study period is compared to that of previous periods studied by Slatis (1953) and Lyster (1971). The similarity and difference between SRB and fertility variation is described, as well as their relationship to temperature and daylength. The loss of amplitude in SRB in the latter stages of the study period demonstrates that the seasonal pattern of SRB has changed from those of earlier periods. I argue that the association of climate and both SRB and fertility must be explored at or near the month of conception.

Selection of climate variables and target populations. Robust linear regression analysis of the sex ratio at birth lagged to the month of conception in high, mid, and low latitude zones among all US births and among white and black populations is used to reduce the slate of climate variables considered for further model building. This analysis considers the impact of selected radiation, precipitation, or temperature climate variables in the month before, during, and the estimated date of conception. This work shows the limitations of OLS regression and narrows the range of climate variables for further consideration. I also resolve the difficulty of controlling for the confounding effects of socioeconomic, cultural, and geographic differences among US population groups shown to have different SRB by focusing the study on births to non-Hispanic white births.

Geographic and seasonal distribution of fertility and sex ratio at birth. I describe seasonal variation of SRB and fertility lagged to conception by broad latitudinal zones and in climate division maps created using spatial Bayes empirical smoothing. Maps of seasonal variation of temperature and precipitation are presented and the possible association of these factors with SRB and fertility during the estimated period of conception is discussed.

Sex ratio, photoperiod, and temperature at conception. I examine in more detail the association of temperature and light at near the time of conception with the probability of conceiving a male. How photoperiod and temperature associations vary by latitude zone is described.

Global model of sex ratio at conception with climate, socioeconomic and individual biological factors. Using the analyses described above, I model the probability of conceiving a male birth using individual factors in association with socioeconomic characteristics of the county of residence and the climate division conditions present at or near the time of birth. Geographic variables are also modeled to control for unspecified spatial variation that may covary with climate or socioeconomic values.

Spatial relationship of seasonal temperature and sex ratio at conception. I construct a local model of sex ratio lagged to conception and seasonal temperatures at the climate division unit of observation using OLS regression and geographically weighted regression. The results of the global logistical regression model and the local spatial model are used to describe the regional and seasonal variation of SRB in the US during the baseline study period of 1979–1988.

Seasonal Variation of Sex Ratio at Birth and Birth Rate in the Study Data

I begin my analysis by retracing the lightly trodden path of previous studies of seasonality and sex ratio at birth in US populations, along with more familiar topic of seasonality and birth rate. A brief review of SRB and birth rate data from the study period compared to those from earlier studies supports my hypothesis that there is a persistent biological pattern to the US sex ratio at birth, and that it has recently undergone change.

Although seasonality in US birth rates has been found in previous studies (e.g., Rosenberg 1966), there is a belief that it has attenuated significantly as the US population labors at nonseasonal work in air-conditioned indoor environments (Seiver 1985). US SRB seasonality has also been found (Slatis 1953, Lyster 1971), but is even less well understood. My results focus on variation in SRB, but support for evidence of seasonal variation in SRB can be found by comparing it to variation in birth rates. Considering the difference in how these two factors vary in relation to each other seasonally and geographically demonstrates that climate continues to be a significant factor in US reproductive ecology.

In the manner of Lyster (1971), I created charts of monthly birth rates and SRB that aggregated multiple year births in two separate periods: 1) all births in 1979–1988 birth data and 2) births from all 458 geographically identified counties in the NCHS 1998–2002 data. For the 1978–1988 period, the annual pattern for both SRB and birth rates is a single-peaked wave (Figure 19). Birth rates have a major peak in August, two months later than the major peak for SRB in June.

When the birth rate is lagged by two months, birth rate and SRB are highly correlated ($r_{pearson}$=0.813, p=0.0013). While the SRB variation from high to low values over each month's aggregated multi-year value is small in percentage terms, it is significant, based on a chi square ordinary goodness of fit test ($\chi^2 = 80.94$, df=11, p<0.0001).

The amplitude size and wave shape in the birth rate during 1998–2002 is very similar to that of the 1979–1988 birth rates (Figure 20), and the relationship of birth rate to SRB during this period is also very similar to that of the earlier period: lagged peaks in SRB (June) and birth rate (August).

The variation of SRB by month aggregated for 1998–2002 is also significant (χ^2= 29.93, df=11, p=0.0016), and also correlated to the birth rate, although to a lesser degree than in the 1979–1988 birth dataset ($r_{pearson}$= 0.672, p=0.016)

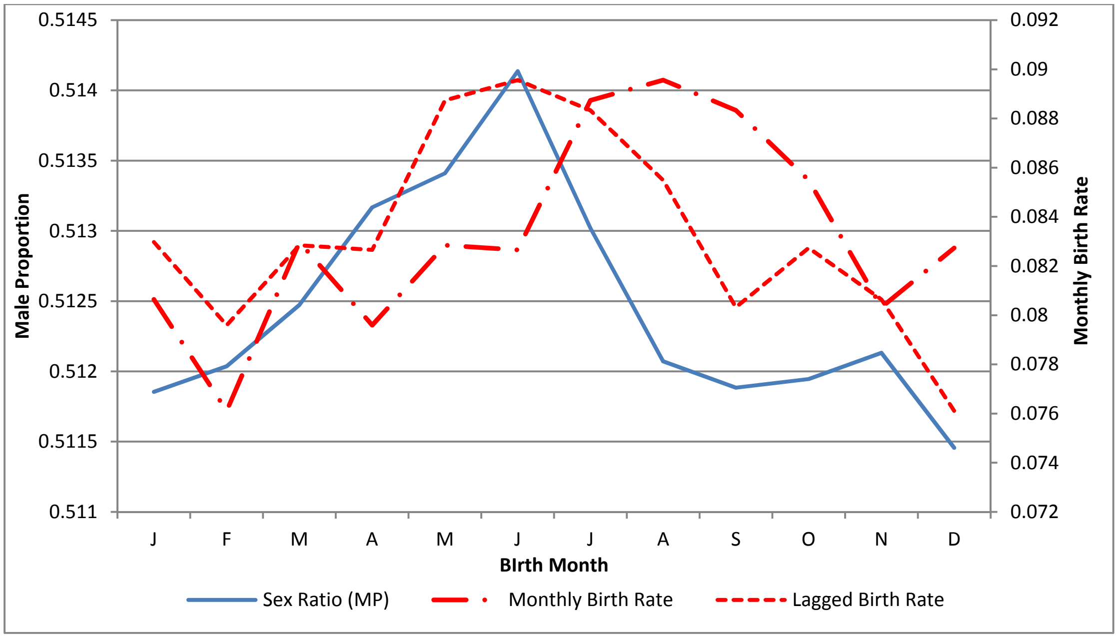

Figure 19. Monthly sex ratio at birth (male proportion) and number of births per month, 1979–1988 births.

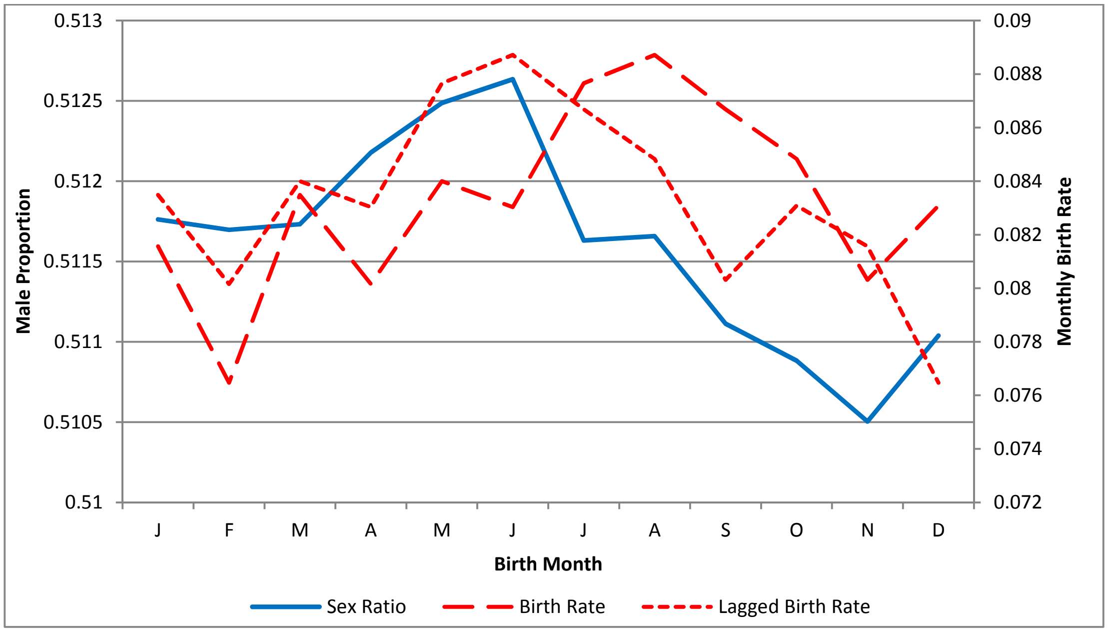

Figure 20. Monthly sex ratio at birth (male proportion) and number of births per month, 1998–2002 births in 458 geographically identified counties.

The month by month alignment of birth rates in 1978–1988 is remarkably similar to that of 1998–2002 ($r_{pearson}$=0.989, p<0.0001), but this stable rhythm should not be surprising to anyone who has made even a cursory study of the seasonality of US birth rates. A seasonal pattern of birth rates with August or September peaks has been documented by various authors since at least the beginning of the last century. The birth rate data from 1979–1988 and 1998–2002 is plotted on Figure 21, along with data from Lyster's 1971 study of the seasonality of sex ratio and birth rate in American births. Although Lyster's data is an estimated fertility rate by month for women between 15–44 and my data includes births to mothers of all ages, the sample population can be considered essentially the same.

Lyster (1971) also found the same two-month lag in peaks of SRB and birth rates. As Figure 22 shows, Lyster's data for the monthly SRB for all US births between 1945 and 1968 show a close correlation to the 1978–1988 pattern ($r_{pearson}$= 0.898, p=0.016). Although monthly data for the 10-year period ending in 1978 is missing from this analysis, it suggests that the seasonality of American SRB has been very stable from the period 1945 to 1988.

However, the monthly SRB for the 1998–2002 period is notably different from the two earlier periods. The 1998–2002 monthly SRB is significantly correlated to the 1979–1988 SRB ($r_{pearson}$ =0.789, p=0.0023) and has the same June peak as the two earlier periods, but it has a lower amplitude than the two earlier periods, and lower values in the latter part of the year compared to the earlier periods. Also, monthly SRB during the 1998–2002 period is lower in every month of the year than it is during the earlier periods. While seasonal birth rate patterns are very similar during this period, there appears to be a significant change in the seasonality of sex ratio at birth during the most recent years of the study period.

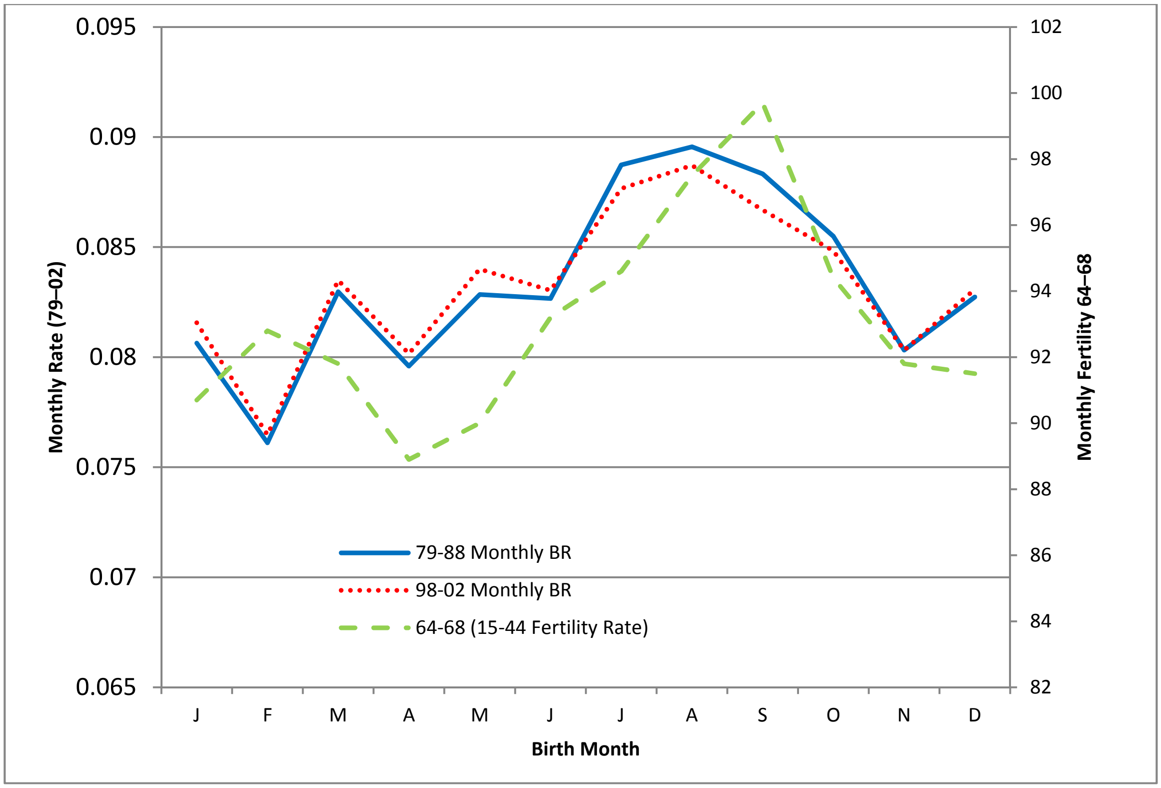

Figure 21. Total monthly birth births for 1979–1988 compared to total monthly births for 1998 to 2002. Monthly fertility rates per 1,000 women 15–44 from Lyster 1971 are indexed on the right axis.

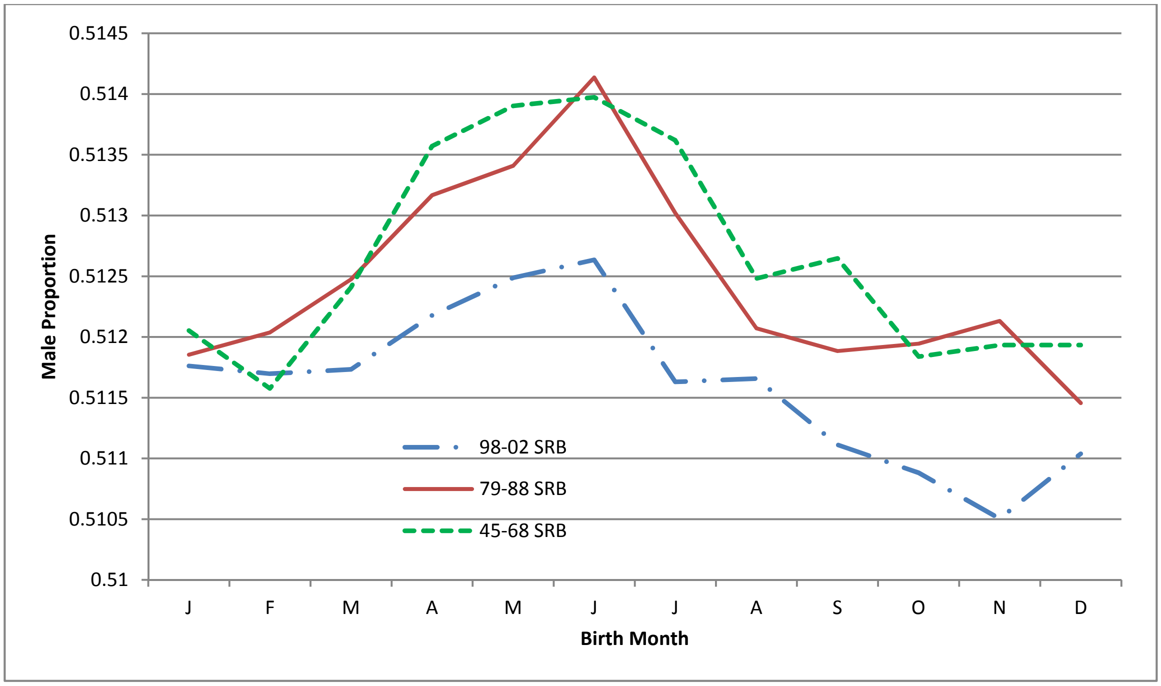

Figure 22. Monthly averages sex ratio at birth for all US births in 1979 to 1988 NCHS data, 1998 to 2002 NCHS data, and 1945–1968 birth data assembled by Lyster 1971.

The seasonality of SRB and birth rates displayed by these data leads readily to hypothesized associations with climate variables, with monthly maxima in daylength and temperature apparently correlated with a high birth rate and of relatively more male births. In the US, seasonal change is marked by changes in the number of daylight hours and by average temperature, both of which have a single major annual peak similar to the patterns of birth rate and SRB. The monthly maximum in the mean number hours between sunrise and sunset (daylength) in any year occurs one or two months prior to the annual monthly maximum monthly temperature, varying depending on latitude, elevation, and other factors. This annual pattern can be seen in the mean monthly aggregation of temperature and daylength for climate divisions in the 1979–1988 dataset (Figure 23).

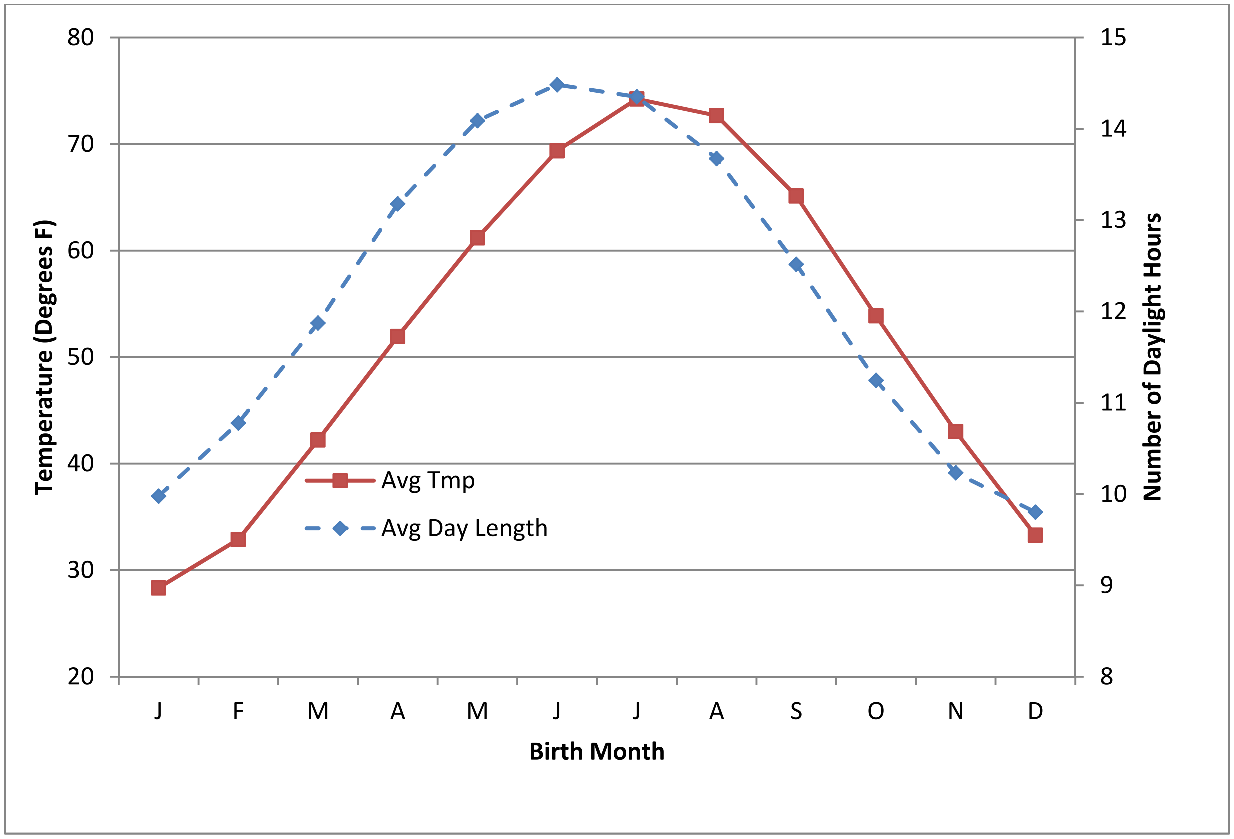

Figure 23. Monthly averages of daylength and temperatures by month, 339 climate divisions, Spring 1978– to Spring 1988.

Using a monthly aggregation over the study period, birth rate and temperature appear to be associated. The 1979–1988 monthly birth rate positively correlates ($r_{pearson}$ = 0.738, p=0.006) with mean monthly temperature, as calculated by averaging monthly values for all climate divisions in the dataset. Similarly, monthly birth rate in the 1998–2002 data rises and falls with average temperature ($r_{pearson}$ =0.713, p=0.009).

However, monthly birth rate does not significantly correlate with the mean monthly daylength in either the 1979–1988 period ($r_{pearson}$ =0.0474, p=0.119) or for 1998–2002 ($r_{pearson}$ = 0.503, p=0.095). On the other hand, daylength is highly correlated in the 1979–1988 data to both the lagged birth rate ($r_{pearson}$ =0.811, p=0.003) and SRB($r_{pearson}$ =0.795, p=0.002). Similarly, in 1998–2002, the two-month lagged monthly birth rate is significantly correlated with monthly average daylength ($r_{pearson}$ =0.772, p=0.003) as is sex ratio ($r_{pearson}$ =0.672, p=0.016). Monthly SRB does not significantly correlate with monthly temperatures during either the 1979–1998 period ($r_{pearson}$ =0.293. p=0.335) or the 1998–2002 period ($r_{pearson}$ =0.296, p=0.349).

These associations suggest the presence of a human reproductive physiology that responds to changes in temperature and photoperiodicity, presumably in tune to the advantageous energy balance that produces abundant food supply and comfortable temperatures for a developing fetus or newborn child. If indeed present, this mechanism persists despite cultural insulation from significant daily or seasonal exposure to these factors. However, the nature of the relationship between human hormonal changes that mediate reproductive and seasonal influences is not clear from the comparisons summarized above. What environmental conditions at the time of conception best foretell a favorable outcome for delivery nine months hence? Why is there a lag between the peak of SRB and birth rate? And most relevant to the focus of this study, are changes in these environmental conditions at the time of conception responsible for the change in the seasonal pattern of SRB in the 1998 to 2002 study period?

The relationship between human sex ratio at birth and birth rate is certainly not clear and may vary by season or location. A number of studies of SRB seasonality have omitted reference to birth rates (e.g., Slatis 1953) or found that seasonal SRB was not related to seasonal birth rate (e.g., Lerchl 1998). However, others have detected significant associations in various countries and climates (Table 4). Like Lyster (1971), some have observed annual SRB peaks that occur before the annual birth rate peak (King 1927, Janerich 1971, Kumari and Rao 1982, and Underwood 1995). The relationship between the peak of male and female births has been found to be inverse by some researchers (Huntington 1938 and Kameri and Rao 1982). Cagnacci et al. (2003) found that sex ratio at conception and birth rate was "in phase" although the theoretical birth rate preceded male conception rate by one month.

Jongbloet et al. (1996) claimed that the annual proportion of female births was highest when birth rate peaked and that male conception peaks occur in a bi-modal or "double humped" pattern around the female peak. They claim to have found this pattern in previous studies by Huntington (1938), Slatis (1953), Lyster (1971) and other data from studies in the US, Canada, Australia, the Netherlands, and Germany. As a partial explanation they cited the early work of Wolda (1927, 1935), who speculated that the seasonality of cattle and pigs and human was similar: males tended to be born early and late during the optimum season for birth and rearing, while females were born at its zenith.

Sex ratio and fertility during the 1979–1988 period are somewhat in phase, similar to that described by Cagnacci et al. (2003), based on the plots I presented at the beginning of the chapter. In the study data, the pattern of the monthly peak of male births occurring prior to the birth rate peak is the same as noted by Lyster (1971) and also conforms several of the studies cited above.

It is also consistent with the "double hump" pattern described by Jongbloet et al. (1996), if the secondary peak of births in November for 1979–1988 births is also considered. The annual temporal relationship between SRB and birth rate therefore bears consideration in the further study of sex ratio decline. However, a deficiency in many of these previous studies is that they do not examine the *conception* season as a factor in the seasonality of delivery.

Table 4. Works comparing sex ratio at conception or birth with birth rate.

Author	Population	Finding related to SRB and Birth Rate
Lyster 1971	US 1964–1968	Two month lag between SRB and birth rate peak.
Kumari and Rao 1982	Hospitals in Vishakhapatnam, India 1972–1974	SRB is affected by climatic variations (monsoon season; temperatures) and sex ratio at birth is inversely related to the birth rate. SRB peaks earlier than conception peak.
Cagnacci et al. 2003	Hospital Modena Italy, 1995–2001	SRB Seasonality is significant but only when lagged to month of conception. Seasonal male conceptions peak in September and correlated to temperature in month before conception. Conceptions peaks in October, "in phase" with male conception peak in September.
King 1927	US Births, 1915–1924; also, 1,983 US families in the Eugenics Study Database (date range unknown), all having four or more children.	US conception birth rate peaks in August and September; SR conception peaks in June, secondary peak in November. Eugenics Births: SRB peak in July, trough in November, second part in October.
Huntington 1938	52 million births in seven countries, around turn of 20th century	Found seasonal coincidence in number of births and number of female births (inverted sex ratio).
Jongbloet et al. 1996	Netherlands, 1902–1938, Germany 1946–1967, Quebec 17th and 18th centuries, Australia, 1911–1962, and US births in Slatis (1953) and Lyster (1971)	Higher frequencies of female peaks and total conceptions around birth optima. Found "double humped" pattern of male peaks on either side of female peak.
Janerich 1971	New York State 1964–1966	SRB peaks in April and July, during troughs in birth rates.
Underwood 1995	Micronesia 1901–1941	SRB peaks in August, troughs in January; Births peak in November; trough in May.

An obvious baseline hypothesis of seasonal fertility is that coital frequency varies seasonally. Spring troughs in births may be partly related to a decrease in coital frequency in the uncomfortable conditions of the summer prior to the birth. Similarly, fall peaks in birth can be attributed to an increase in coital frequency during the Thanksgiving and Christmas festival season. Seiver (1985) suggested that heat and humidity was a depressing factor on summer conceptions, resulting in the April trough in US births. He found that the amplitude of seasonal change, most pronounced in the southeast US, diminished in recent decades with widespread use of air conditioning. Wedding patterns may also be a cultural influence. Between 1920 and 1991, the monthly patterns of first births in an Ohio community of Old Order Amish was found to be highly influenced by the seasonal pattern of weddings nine months previous, and was almost identical to the US pattern as a whole in the early 1940s, before air conditioning was widely adopted (Gresksa 2004). These data suggest that season patterns of coital frequency are at least partially cultural in origin.

However, Seiver (1985) also speculated that seasonal variation in hormones or other reproductive mechanisms was a factor in fecundity. Seasonality has been found to be a factor in the number of ovulations, the quality or volume of semen, and rates of embryo mortality. Because seasonality effects are different between woman and men, the problem of how to identify seasonal hormonal variation as a factor in fertility is further complicated. Less immediate but related causes of variation with seasonal components include age at first coitus, age of first menarche, length of menstrual cycle, frequency of spontaneous abortions, success rate of artificial insemination, rates of congenital deformities and other physical characteristics such as height, weight, and chest circumference, the rates of twinning, and duration of the period in which nursing protects against further insemination (lactational amenorrhea).

The season of birth can also affect future health, such of the incidence of breast cancer (Yuen et al. 1994, Nakao et al. 1987), schizophrenia (Verdoux et al. 1997) and overall longevity. Miura et al. (1987) suggested that the month of the mother's birth affects birth seasonality, with mothers born during the low-birth-rate seasons more immune to factors that caused spontaneous abortions to mothers born in other seasons.

In assessing birth rates and SRB, it is important to consider that intervening seasons between conception and delivery might take a different toll on each gender. I have cited evidence that females in general negotiate the perils of gestation journey more adroitly than do males and thus may survive difficult seasonal conditions better. As noted above, Cagnacci et al. (2003) did not find significant seasonal variation in SRB stratified by month, but such variation was readily detected in the sex ratio at the month of conception. Using gestational age to estimate the month of conception, they found that the sex ratio of fetuses born between 30 and 37 weeks was significantly higher than those born at 40–42 weeks (0.525 v. 0.498; $\chi 2$, $p<0.02$) , with intermediate values found for those born between 38–39 weeks of gestation.

In the 1978–1988 birth data there are seasonal patterns of sex ratio variation in preterm births, those occurring prior to 37 weeks of gestation (Figure 24). The SRB of all pre-term births is very high (>0.533) compared to the mean sex ratio for all births, but is highest in the summer season. This is also the season of the highest number of preterm births, which show an even sharper rise in frequency compared to other seasons than does SRB. This sharp increase in preterm births during the summer months agrees with other seasonality studies of gestation sex ratio. Keller and Nugent (1983) found in a study of Minnesota births that preterm births were more likely in July, August and September. They also found that the highest occurrence of perinatal mortality also occurred during these months. Consideration of the seasonal variation in gestational ages in newborns is thus an important factor in evaluating the seasonality of SRB and birth rate.

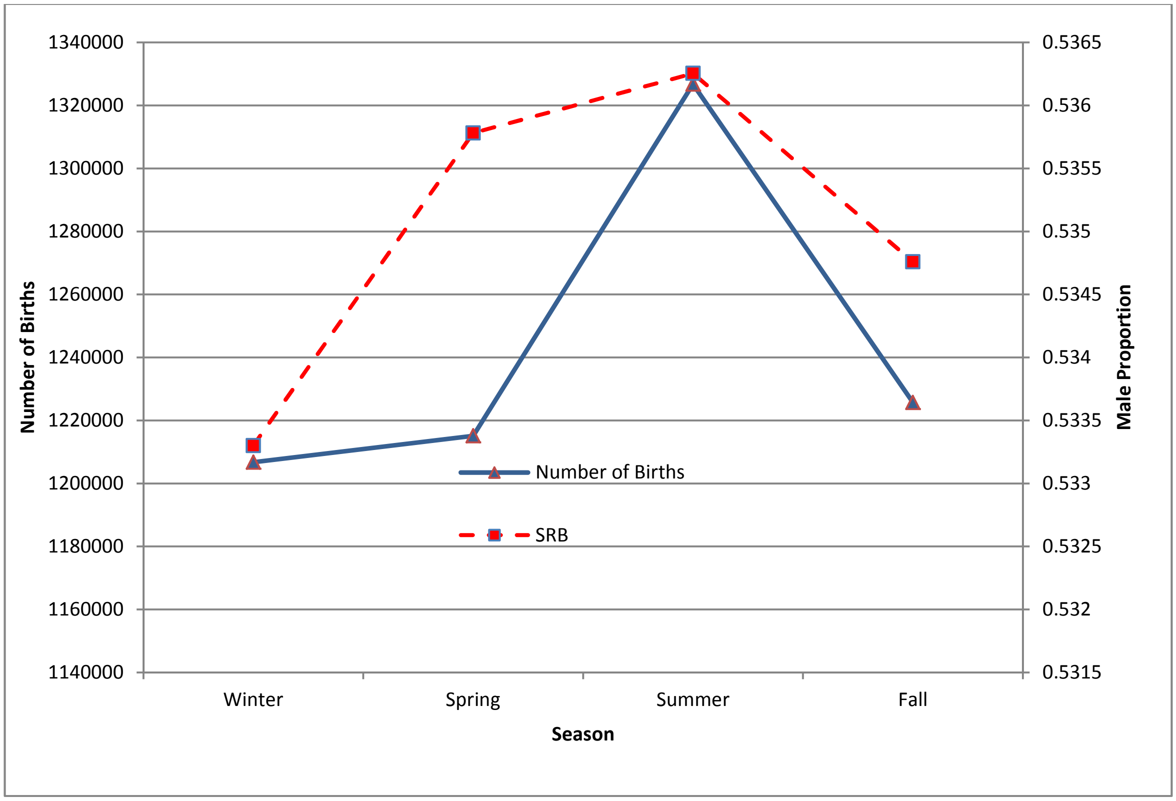

Figure 24. Sex ratio at birth and number of preterm births by season, 1979–1988 birth data (n=4,974,379).

Selection of Climate Variables and Target Populations

Linear Regression Analysis by Population Group and Climate Variable Type

When they examined the role of gestational age differences in seasonal birth variation in metropolitan Atlanta, Darrow et al. (2009) found that seasonal patterns differed among racial and ethnic groups, maternal education levels, and marital status and that these confounding differences complicate the investigation of seasonal influences in any geographic location. Race, ethnic origin, and marital status have also been found to be significant in SRB variation (James 1987a, Norberg 2004, Branum et al. 2009). The SRB for race, ethnic origin, and birth order/plurality in the 1979–1988 dataset (**Error! Reference source not found.**) agree with the relative relationships consistently reported by NCHS (e.g., Mathews and Hamilton 2005) and in other studies of biological and cultural factors that may bias sex ratio at birth.

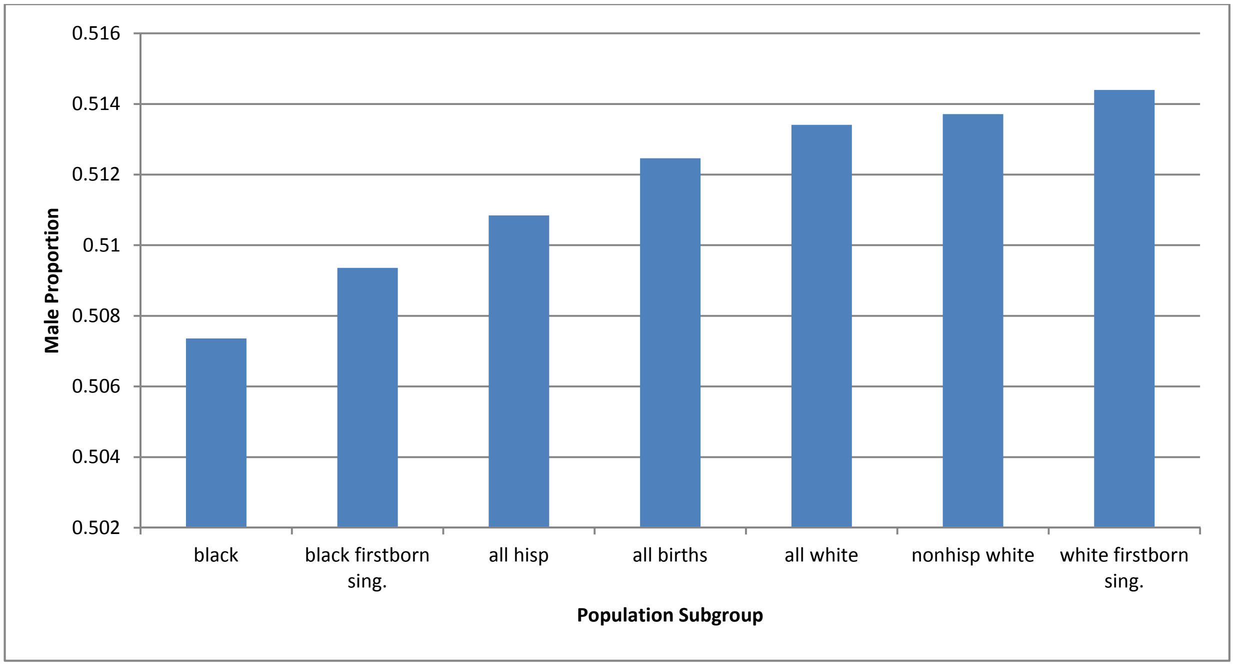

Figure 25. Sex ratio of all births in 1979–1988 NCHS dataset, compared with selected subpopulations classed by race of mother (white, black), origin of mother (all Hispanic, all races (all hisp), and firstborn, singleton status (firstborn sing).

My initial approach to exploring the relationship of climate to sex ratio was to test associations between these population subgroups and the slate of climate variables I had selected as possible factors of influence. To reduce the initial list of climate variables to a manageable one for further analysis, I aggregated sex ratios for selected population groups as the dependent variable in regressions using temperature (TMP), heating and cooling days (CDD, HDD), precipitation volume (PCP) and drought conditions (ZNDX, PMDI, PHDI), and indices of direct and diffuse solar radiation occurred during the estimated month of conception (AVGLO, AVDIR, AVDIF, TOT). Normalized scores for deviation from monthly values (e.g., ZTMPZ, ZPCP) were also analyzed. In each case, sex ratio lagged to estimated conception month was regressed against the climate value for that month, as well for preceding month (B_x) and following month (A_x). (See Table 1 in the preceding chapter for a list of variables and sources).

These associations were tested in a linear regression model using the Huber M robust regression method in SAS. This method was chosen to reduce the influence of residuals, especially for births to black mothers, which have a different geographic area of distribution than the white population or US population as a whole (see Figure 18). Each model consisted of a single monthly climate factor as the independent variable and the estimated monthly sex ratio at conception for all births, births to white mothers, or births to black mothers as the dependent variable. To reduce the effects of the biological factors of multiple births and birth order, I also analyzed firstborn, singleton births within these subpopulations. In addition, I created three broad US latitude zones similar to those used by Lam and Miron (1987) to report the differing amplitude of monthly conception rates by latitude in US births. The mean latitude value for the centroids of all climate divisions in this dataset (39.32 degrees N) is near the latitude of the geographic center of the continental US (39.49 degrees N). I rounded this value up and used 40 degrees N to define a boundary above which climate divisions were considered in the high latitude; 35 degrees was used to demark low and mid-latitudes (**Error! Reference source not found.**).

A summary of these models is presented below for all births (Table 5), all white births and singleton, first born white births (Table 6) and all black births and singleton firstborn black births (Table 7). On first examination, these data seem to show significant influences on sex ratio in each of the tested populations, although the magnitude and direction of each climate variable is frequently different. Increases in temperature (TMP, ZTMP) before and after conception appears to significantly increase the number of male births in mid-latitudes, while precipitation and drought (ZNDX, PSDI, PMDI, PHDI) appears to be the most influential factor in low latitude births. Similarly, heating degree days (HDD) are negatively correlated with birth while cooling degree days (CDD) are associated with an increase in births. In general, a significant association of climate variations and sex ratio occurs more frequently in the month before or during conception than it does after.

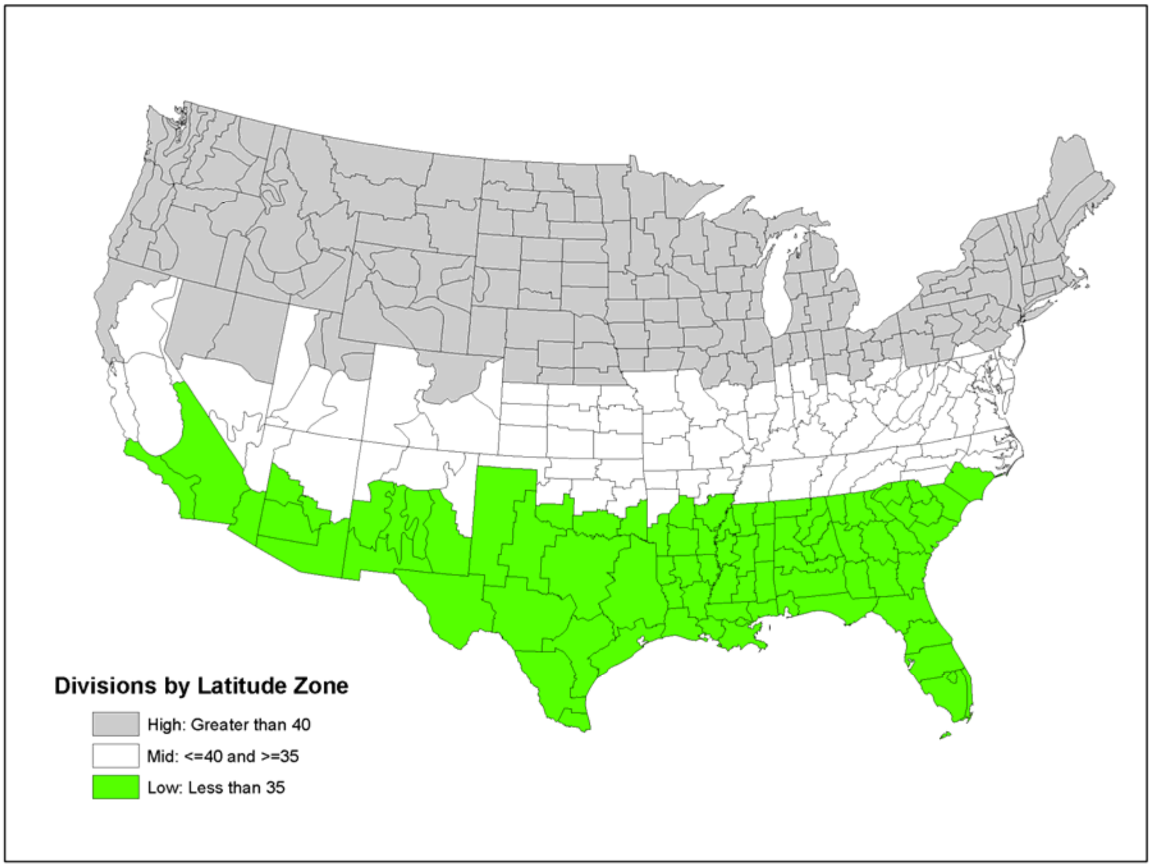

Figure 26. Climate divisions divided by three broad latitudinal bands: High (greater than 40 degrees), Mid (<=40 and >=35 degrees), and Low (<35 degrees).

Table 5. All Births: Univariate robust regression analysis (Huber M – SAS) of sex ratio at conception (DV) and climate variables (IV) at time of conception for all births 1979–1988. Precipitation variables are in regular font, temperature variables are in bold, and radiation variables are in underline italics.[3] Results shown only for variables with results $p<0.05$.

Latzone	N	Climate Variable	Estimate	Std Err.	-95% CI	+95% CI	Chi Sq	P>Chi Sq
High	**19551**	**A_ZTMP**	0.0585	0.0233	0.0128	0.1042	6.29	0.0121
High	19551	*A_AVGLO*	0.0000	0.0000	-0.0001	0	4.7	0.0301
High	19551	*A_AVDIR*	0.0000	0.0000	-0.0001	0	8.6	0.0034
Mid	11520	**B_TMP**	0.0038	0.0015	0.0009	0.0068	6.43	0.0112
Mid	11520	**B_CDD**	0.0004	0.0001	0.0002	0.0007	12.1	0.0005
Mid	11520	**CDD**	0.0004	0.0002	0.0001	0.0008	6.32	0.0119
Mid	11520	**B_HDD**	-0.0001	0.0001	-0.0003	0	4.89	0.0271
Mid	11520	*B_AVDIF*	0.0001	0.0000	0	0.0002	4.52	0.0335
Mid	11520	A_ZPCP	-0.0642	0.025	-0.1132	-0.0151	6.57	0.0104
Mid	11520	A_ZNDX	-0.0357	0.0127	-0.0606	-0.0107	7.84	0.0051
Mid	11520	A_PDSI	-0.0232	0.011	-0.0447	-0.0017	4.46	0.0346
Low	9600	**B_TMP**	0.0042	0.0017	0.0008	0.0076	5.82	0.0159
Low	9600	**B_CDD**	0.0004	0.0002	0.0001	0.0008	6.6	0.0102
Low	9600	B_ZPCP	-0.0509	0.0243	-0.0985	-0.0033	4.39	0.0362

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[3] Climate variables: Prefix "A_" indicates monthly measure after month of conception; Prefix "B_" is monthly measure in month before conception; TMP: mean monthly temperature; ZTMP: standardized monthly temperature; AVGLO: average daily global radiation; AVDIR: average daily direct radiation; AVDIF: average daily diffuse radiation; CDD: cooling degree days; HDD; heating degree days; PCP: monthly precipitation; ZPCP: standardized monthly precipitation; ; ZNDX: Palmer Drought Z Index; PHDI: Palmer Hydrological Index; PDSI: Palmer Draught Severity Index; PMDI: Modified Drought Severity Index. See Table 1 for more detail.

Table 6. White Births: Univariate robust regression analysis (Huber M – SAS) of sex ratio at conception (DV) and climate variables (IV) at time of conception for births whose mother identified as white in NCHS births 1979–1988 data. Precipitation variables are in regular font, temperature variables are in bold, and radiation variables are in underline italics (see footnote 3 at end of Table 6 for abbreviation guide). Results shown only for p<0.05.

All White Births

Latzone	N	Climate Variable	Estimate	Std Err.	-95% CI	+95% CI	Chi Sq	P>Chi Sq
High	19551	**A_ZTMP**	0.059	0.0241	0.0117	0.1062	5.99	0.0144
High	19551	*A_AVGLO*	0	0	-0.0001	0	4.4	0.0359
High	19551	*A_AVDIR*	0	0	-0.0001	0	6.94	0.0084
Mid	11520	**B_TMP**	0.004	0.0017	0.0007	0.0072	5.68	0.0172
Mid	11520	**CDD**	0.0005	0.0002	0.0002	0.0009	7.82	0.0052
Mid	11520	**B_CDD**	0.0005	0.0002	0.0001	0.0008	6.39	0.0115
Mid	11520	**A_CDD**	0.0004	0.0002	0	0.0007	4.16	0.0414
Mid	11520	**B_HDD**	-0.0001	0.0001	-0.0003	0	4.07	0.0437
Mid	11520	A_PDSI	-0.0242	0.0121	-0.0479	-0.0005	3.99	0.0457
Low	9600	**B_CDD**	0.0004	0.0001	0.0001	0.0007	6.22	0.0126
Low	9600	B_ZPCP	-0.0787	0.0299	-0.1373	-0.0202	6.94	0.0084
Low	9600	B_ZNDX	-0.0409	0.0151	-0.0705	-0.0113	7.32	0.0068
Low	9600	B_PMDI	-0.0349	0.0138	-0.0619	-0.0079	6.4	0.0114
Low	9600	A_PMDI	-0.0289	0.0138	-0.0559	-0.0018	4.38	0.0363
Low	9600	PMDI	-0.0354	0.0138	-0.0624	-0.0084	6.59	0.0103
Low	9600	PDSI	-0.0296	0.0136	-0.0562	-0.003	4.74	0.0294
Low	9600	B_PDSI	-0.0295	0.0136	-0.0561	-0.0029	4.73	0.0297

White Singleton First Born Births

High	19384	**A_ZTMP**	0.0831	0.0388	0.007	0.1592	4.58	0.0324
Low	9581	B_ZNDX	-0.0492	0.0228	-0.0939	-0.0045	4.65	0.031
Low	9581	PMDI	-0.0522	0.0208	-0.093	-0.0115	6.3	0.0121
Low	9581	B_PMDI	-0.0609	0.0208	-0.1017	-0.0201	8.57	0.0034
Low	9581	A_PHDI	-0.0446	0.0196	-0.0829	-0.0062	5.19	0.0227
Low	9581	B_PHDI	-0.0583	0.0195	-0.0966	-0.02	8.91	0.0028
Low	9581	PHDI	-0.0556	0.0195	-0.0939	-0.0173	8.1	0.0044
Low	9581	PDSI	-0.0487	0.0205	-0.0889	-0.0086	5.66	0.0174
Low	9581	B_PDSI	-0.0546	0.0205	-0.0948	-0.0145	7.1	0.0077

Table 7. Black Births: Univariate robust regression analysis (Huber M – SAS) of sex ratio at conception (DV) and climate variables (IV) at time of conception for births to mothers identified as black in NCHS 1979–1988 data. Precipitation variables are in regular font, temperature variables are in bold, and radiation variables are in underline italics (see footnote at end of Table 5 for abbreviation guide). Results shown only for p<0.05.

Latzone	**N**	**Climate Variable**	**Estimate**	**Std Err.**	**-95% CI**	**+95% CI**	**Chi Sq**	**Pr>Chi Sq**
All Black Births								
Mid	9194	A_ZPCP	-0.1636	0.0816	-0.3235	-0.0037	4.02	0.0449
Low	8872	**B_HDD**	-0.0004	0.0002	-0.0007	0	4.27	0.0389
Black Singleton First Born Births								
High	7464	*A_AVDIR*	-0.0002	0.0001	-0.0003	0	4.71	0.0301
High	7464	*AVDIR*	-0.0002	0.0001	-0.0003	0	4.54	0.0332
High	7464	*TOT*	0.2225	0.1058	0.0151	0.4298	4.42	0.0355
High	7464	*A_TOT*	0.2332	0.1055	0.0264	0.44	4.89	0.0271
High	7464	PCP	0.1327	0.0611	0.0129	0.2525	4.71	0.0299
High	7464	B_PCP	0.1288	0.0612	0.0088	0.2488	4.43	0.0354
Low	8510	ZNDX	0.0798	0.0385	0.0044	0.1552	4.3	0.0381
Low	8510	PCP	0.0564	0.0277	0.002	0.1108	4.13	0.042
Low	8510	ZPCP	0.1716	0.0756	0.0235	0.3196	5.16	0.0232

The relationships between single climate variables and sex ratio at conception suggest that temperature and precipitation may be associated with seasonal changes in all US births. However, after considerable further exploration of the spatial and temporal variation of SRB by climate variable within these populations, I abandoned my original plan to track the relationship of climate on the spatial and temporal patterns SRB of each of these populations. I also concluded that the linear regression model sheds more heat than light, as it were, on these relationships. For example, the difference in white and black population geographic distribution, as demonstrated in the previously discussed Figure 15, makes comparisons between populations within a latitude zone invalid. Each population has different concentrations across and between latitude zones and are thus experiencing different climate regimes. Further, this method does not address how social and economic conditions potentially influencing sex ratio might independently vary among white and black populations within their respective geographic distributions. In addition, although the Huber-M analysis reduces the influence of residuals, a large number of climate division months with low total births remain in the analysis; these are the entire population of residuals. In the black birth population, for example, climate division months with a total of three births and ratios of 33 or 66 percent represent large spikes on a histogram for this period (Figure 18, previously discussed). Even with robust regression adjustments, there is a high degree of heteroscedasticity in this model resulting from high and low sex ratio values of the low population climate months flaring at either end of the regression line. Finally, the potential for spatial autocorrelation is also not addressed in this approach.

Spatial Clustering Analysis of White SRB

To concentrate on the spatial and temporal variation of sex ratio at birth primarily associated with climate variables, I focused further analysis on the births to white mothers, which are present in all climate divisions. To detect spatial and temporal clusters of high and low values of sex ratio in the white population for the 1979-1988 study period, total numbers of boy and girl births for each climate month were examined for clustering using SatScan software. Using the Bernoulli model of SatScan, male births were designated as cases and female births as controls for the 339 divisions over the 1979–1988 study period. A search was defined for either high (male birth cluster risk or CLU_RISK>1) or low (female birth or CLU_RISK<1) value clusters not exceeding 50 percent of the study area; 999 permutations of the Monte Carlo based simulation were run to determine significance of identified clusters. The result of this analysis is a single significant cluster area of low sex ratio (CLU_RISK<1, p=0.03) located in the southwest US. Because Hispanic white births are also concentrated in this area (Figure 27) and the SRB of Hispanic births has been reported as consistently lower than that of non-Hispanic births, the significance of this cluster is most likely not a climate effect but rather the geographic concentration of a subpopulation with consistently lower SRB (see Branum et al. 2009 or Mathews and Hamilton 2005). Repeating the analysis with only non-Hispanic white births, no significant spatial clusters of sex ratio were found for the study period using this method. Based on this result, the primary study population was reduced to non-Hispanic white mothers.

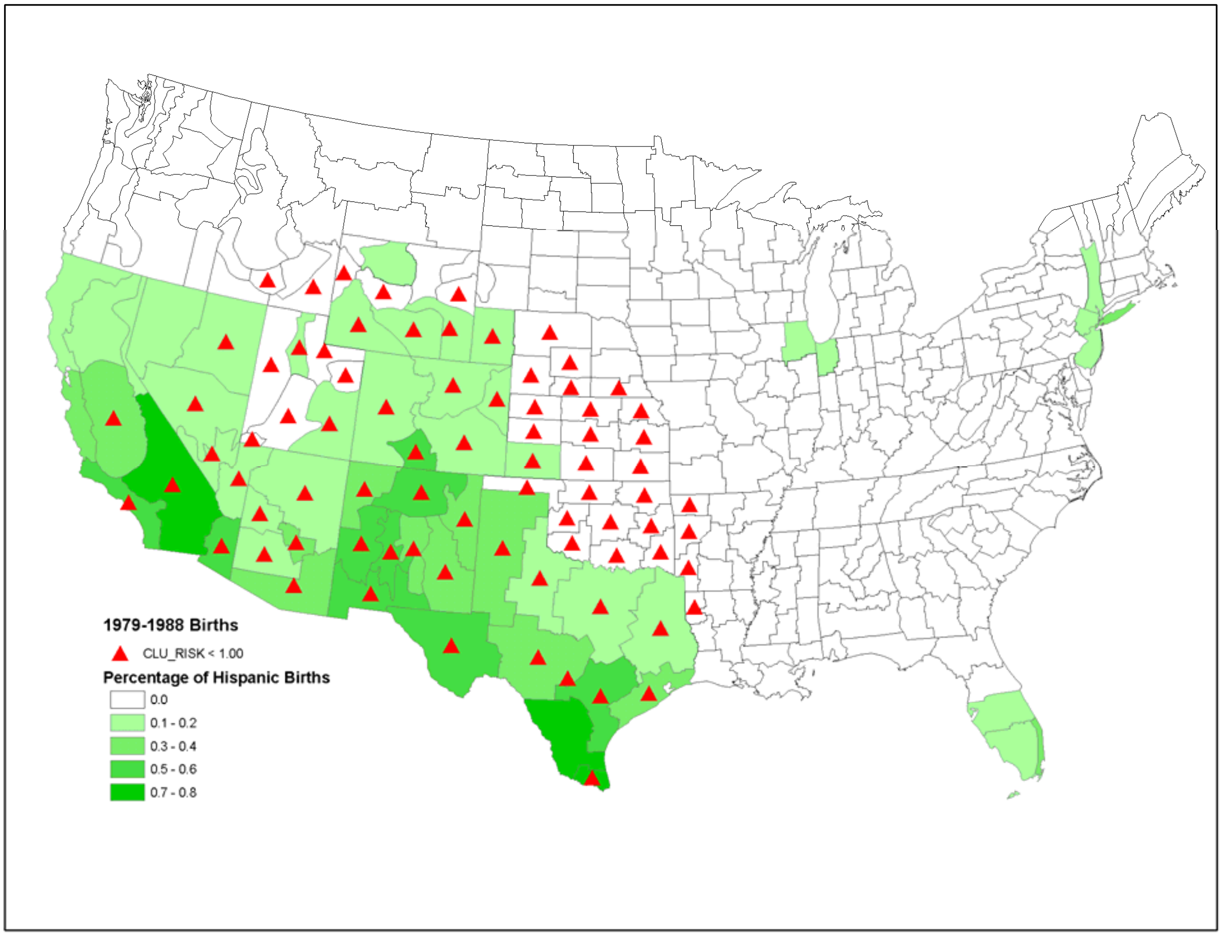


Figure 27. 1979–1988 climate division percentage of births to white non-Hispanic mothers and divisions with significant concentrations of low white SRB (Percentages of births based on ORMOTH and MRACE fields in NCHS data. Cluster values based on space/time StatScan analysis of SRB by division and month, Bernoulli model, using number of boys as cases and number of girls as controls, spatial clusters not exceeding 50 percent of study area, 999 iterations, cluster risk (CLU_RISK<1.00, p =0.03)).

Rather than further attempt to resolve the issues associated with robust linear regression analysis of climate division observations of SRB, I used the OLS linear regression tool of GeoDa to assess the influence of climate variables on non-Hispanic white births. While this software does not have a robust regression adjustment, it does produce spatial autocorrelation diagnostics.

To reduce the effect of residuals produced by low-population climate division month, I aggregated total births by season, creating Winter, Spring, Summer and Fall datasets each containing all births to non-Hispanic white mother during the respective season for the total 1979–1988 period. The GeoDa spatial lag function requires a geographic weight file, which I created using a threshold distance function using Euclidean distance and the x and y centroids of the 339 divisions, which is appropriate for the projected surface of this shapefile. I accepted the minimum threshold distance calculated by the program (approximately 310,000 meters). For comparison, I also ran the model with a Queens and Rooks contiguity weight using one order of contiguity, that is, climate divisions immediately bordering. Essentially the same results were produced with all these weighting methods, although the Queen and Rooks contiguity weight methods were less likely to report spatial autocorrelation than the threshold distance model.

As with the SAS robust regression model, the GeoDa OLS regression analysis with spatial diagnostics was conducted for each monthly climate factor as a single independent variable against the corresponding monthly estimated sex ratio at conception for non-Hispanic white births (Table 8). Temperature (TMP) during the month of conception, and temperature in the month before (B_TMP) have significant positive association with sex ratio at birth in both the summer and fall. The R^2 value for these univariate analyses is low, but tiny variation is the arena in which sex ratio research operates. The correlated temperature variables of cooling degree days and heating degree days also confirmed a positive relationship between ambient temperature and sex ratio: as cooling degree days went up, indicating greater demand for air conditioning, so did sex ratio values; similarly, there is a negative association between sex ratio and heating degree days in the month before conception (B_HDD).

Table 8. Influence of climate variables by season, non-Hispanic white births, 1979–1998, univariate OLS regression with spatial diagnostics.

Climate Variable	Coefficient	St Err	t-Statistic	P>t	r2	Breusch-Pagan P	Spatial Diag. P	White P
Winter: Mean SR 0.51364 SD:0.00777015								
None								
Spring: Mean SR: 0.513654 SD 0.00861056								
None								
Summer: Mean SR: 0.513388 SD: 0.00858654								
A_TMP	0.00016	7.14E-05	2.2999	0.0220645	0.015	0.000	No	0.000
CDD	0.00001	0.000003	1.965171	0.050	0.011	0.094	No	0.042
B_TMP	0.00016	0.000070	2.238906	0.026	0.015	0.000	No	0.000
A_HDD	-0.00003	0.000008	-3.10369	0.002	0.028	0.000	No	0.000
Fall: Mean 0.514334 SD:0.00815091								
TMP	0.00012	0.000053	2.245588	0.025	0.015	0.011	No	0.072
A_TMP	0.00010	0.000046	2.203662	0.028	0.014	0.024	No	0.024
A_ZTMP	0.00701	0.003409	2.057002	0.040	0.012	0.294	No	0.011
A_AVGLO	0.000002	0.000001	1.963249	0.050	0.011	0.026	No	0.073
B_HDD	-0.00001	0.000004	-2.61751	0.009	0.020	0.000	No	0.141
A_HDD	0.00000	0.000002	-2.26803	0.023	0.014	0.002	No	0.199
B_TMP	0.00014	0.000062	2.336284	0.020	0.016	0.039	No	0.057

Climate variables: Prefix “A_” is measure month after conception; Prefix “B_” is measure month before conception; TMP: monthly temperature; Z_TMP: standardized monthly temperature; CDD: cooling degree days; HDD: heating degree days; AVGLO: average daily global radiation. See Table 1 for detail.

The highest coefficient of any climate variable in these regressions is the increase in sex ratio associated with an increase in z-score of the temperature in the month following conception. The z-score is the standardized value of monthly temperature compared with its 1971–2000 monthly mean value (A_ZTMP). In this analysis, no significant associations with climate variables during winter or spring were found.

No significant spatial dependence (spatial diag P) was found in these single variable models, providing some additional confidence that climate variation, particularly changes in temperature at the time of conception, has a significant relationship to variation in sex ratio at birth. However, significant results for the Breusch-Pagan and White tests show that heteroscedasticity remains an issue with this approach, probably because additional specification of explanatory factors is needed. This model does not consider, for example, that such individual factors as gestation period, birth order or the plurality of birth might vary regionally or seasonally. More understanding of geographic and seasonal variation is also needed, especially of the relationship between temperature and estimated sex ratio at conception. As the analysis of monthly aggregation of sex ratio and fertility values showed, a historical pattern of seasonality for these factors persists to some degree in the study period. While the geography of birth rate variation has been studied in some detail (Lam and Miron 1996, Seiver 1985), the spatial variation of sex ratio at birth in the US is not well understood.

For this more detailed geographic analysis I again use seasonality of birth rates as a touchstone for considering the seasonality of sex ratio. I begin by plotting monthly conception birth rates by high, mid, and low latitude zones as mapped in previous **Error! Reference source not found.** for 1979–1988 non-Hispanic white births (see Figure 28). Again, there is a consistent rhythm in birth rates; here it can be seen that it persists across broad latitude zones of the US. The month to month correlations among all three zones are remarkably high (high and mid: $r_{pearson}$ =0.925, $p < 0.0001$; high and low: $r_{pearson}$ =0.771, $p=0.0033$; mid and low: $r_{pearson}$ =0.948, $p<0.0001$). There are some noteworthy differences in the relative amplitude of these three zones, however. The conception birth rates for high latitudes are relatively greater than either the mid or low latitudes between May and September, while low latitudes have relatively higher conception rates between November and April. The birth rate for the mid latitude zones falls between these zones for all months except October, where it has the highest monthly rate of the three zones.

For all three latitude zones, December has the highest rate of conceptions, with a minor peak persisting into January. Summer appears to be relatively more advantageous for high latitude conceptions than it is for those in lower latitudes. The similarity in minor peaks in March and October in all three zones is also worth noting.

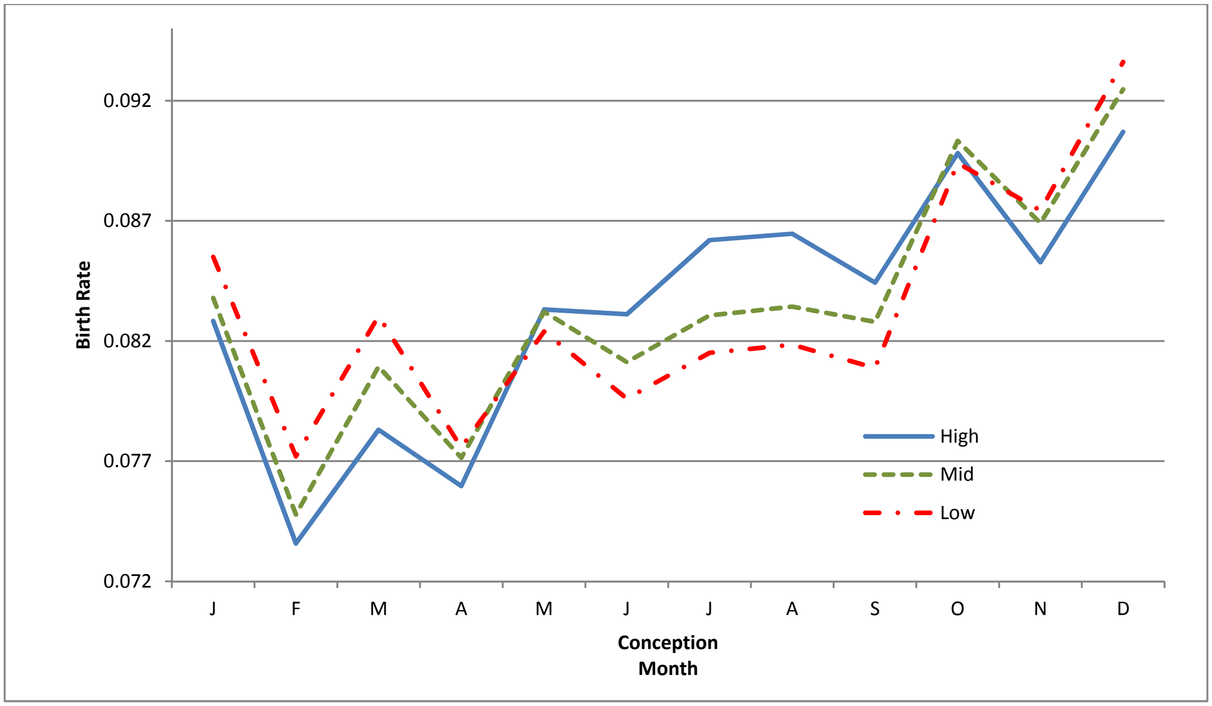


Figure 28. Rate of conception by month and high, mid, and low latitudes for non-Hispanic white US births conceived 1979–1987.

The monthly variation in estimated sex ratio at conception for non-Hispanic white births for the 1979–1988 study period is more chaotic than is the pattern of conception rates (Figure 29). Seasonality of sex ratio is frequently not apparent in studies of monthly values, but may appear when aggregated by season (e.g., Kumari and Rao 1982); therefore I added a three-month moving average trend line to the monthly values. The moving average trendlines show that conception sex ratio peaks during the latter part of the year, with a higher amplitude of annual change in the low latitude zone compared to the high latitude zone.

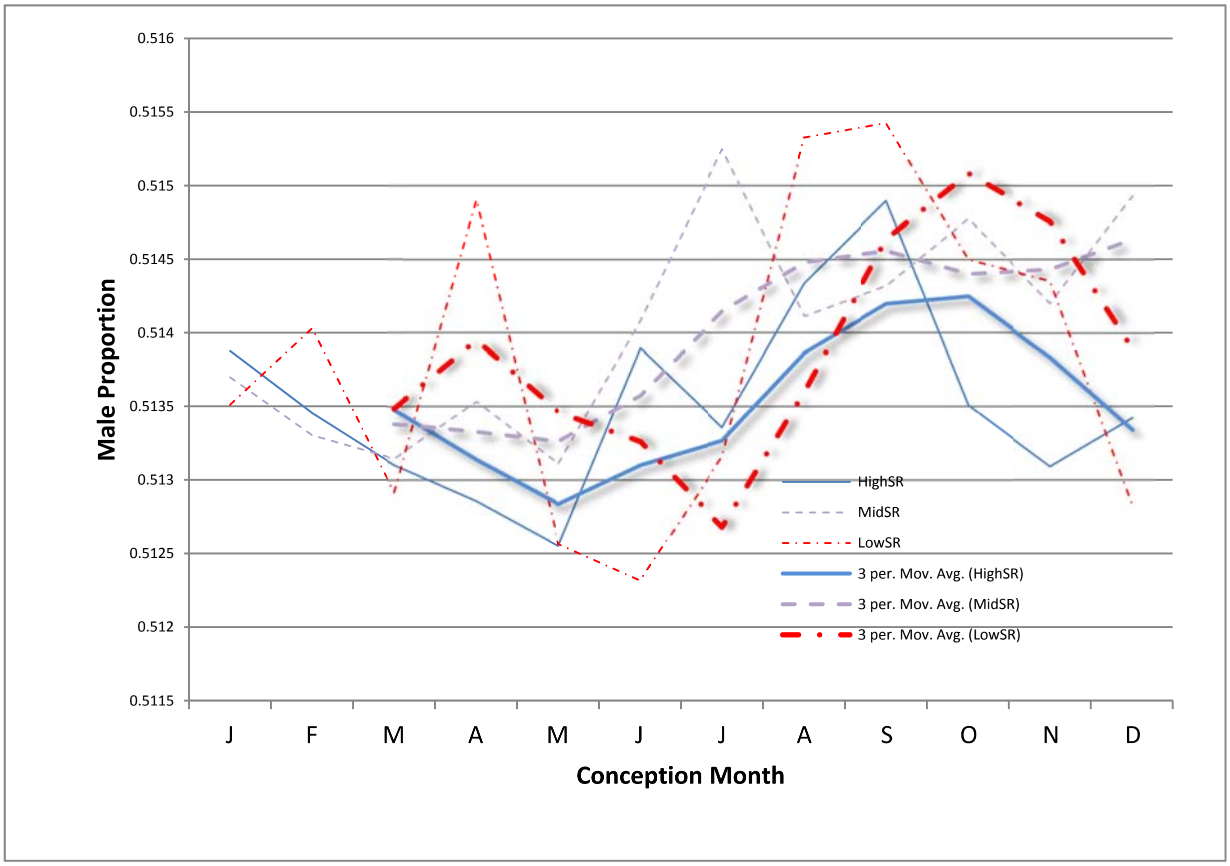


Figure 29. Monthly average of sex ratio at birth for non-Hispanic white US births conceived 1979–1987 by high, mid, and low latitudes with three-month moving average trendlines.

The relationship of sex ratio to fertility across latitude zones is also more apparent when aggregated by season. Seasonal conception birth rates and sex ratio are compared by latitude in Figure 30. To reduce the possible trailing effects of preterm and postterm births that might bias the SR in the aggregated seasonal analysis, I selected only non-Hispanic white conceptions calculated to occur between December 1979 and November 1987, a nine year period. With record weights, total conceptions represented in this analysis are 10,569,370 (high), 6,031,619 (mid), and 5,520,315 (low), or a total of 22,121,304.

As this figure shows, sex ratio and birth rate lagged to conception season are highly correlated when all seasonal values for all latitude zones are considered as a group ($r_{pearson} = 0.77$, p=0.031). However, only the low latitude zone correlation is significant when each zone is considered separately (high: $r_{pearson} = 0.88$, p=0.11; mid: $r_{pearson} = 0.80$, p=0.19; low: $r_{pearson}=0.96$, p=0.03). Among all zones, fall and spring sex ratio and birth rates are most highly correlated (fall: $r_{pearson} = 0.99$, p=0.03; spring: $r_{pearson} = 0.999$, p=0.008), while summer and winter values are most out of phase (summer: $r_{pearson} = -0.56$, p=0.61; winter: $r_{pearson} = 0.51$, p=0.65). Although non-significant, the summer sex ratio/birth rate correlation is negative.

When sex ratios are aggregated by latitude zone, they form a significant trend from north to south (high: 0.5134; mid: 0.5138; low: 0.514; Mantel-Haenszel Chi-Square=6.1581; p=0.013). This is similar to the gradient found by Grech et al. (2000) in western Europe. These authors suggested that an association between increasing temperatures and increased sex ratio was the cause. However, this analysis shows summer temperatures are more relatively favorable to male conception in northern latitudes than in southern ones in US births. Preference for summer as a conception season in general also diminishes as latitude decreases. The next section will explore this variation in greater geographic detail.

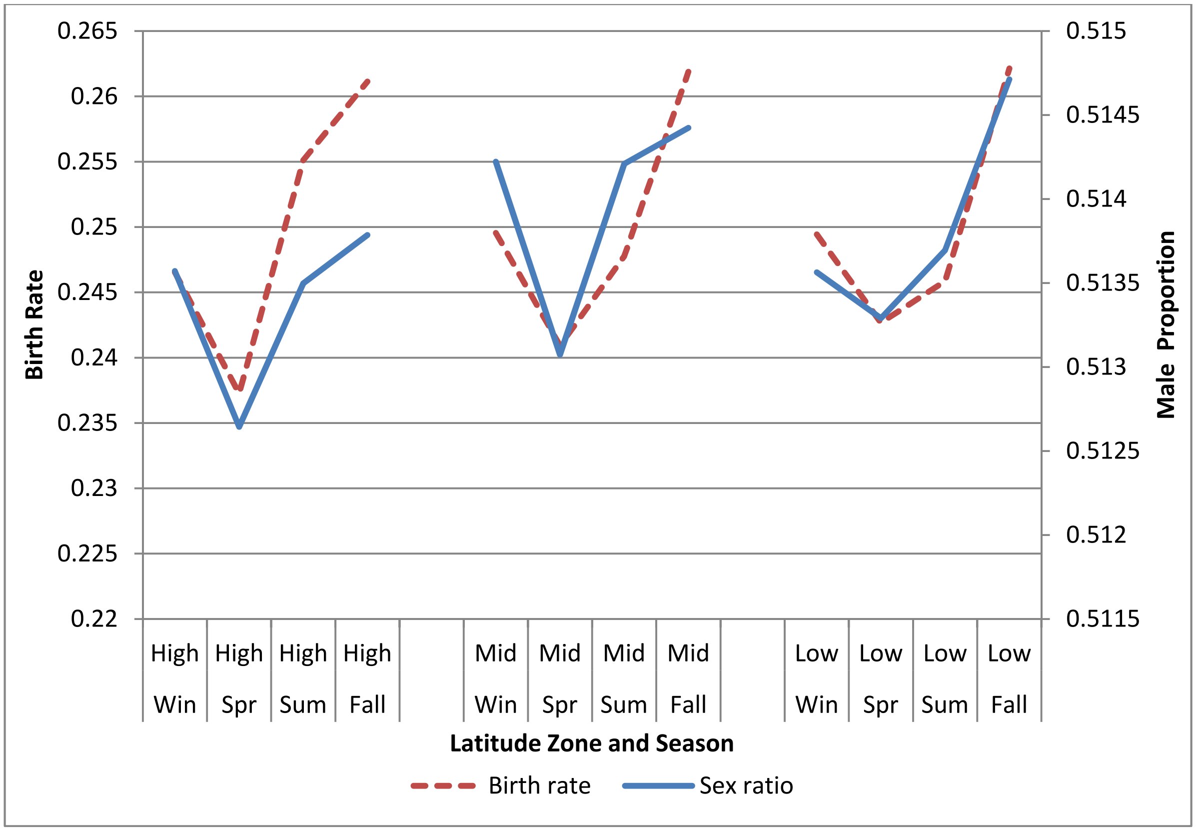


Figure 30. Estimated seasonal rate of conception and sex ratio at conception by high, mid and low latitudes, non-Hispanic white US births conceived 1979–1987.

Geographic Distribution of Seasonal Birth Rates and SRB Lagged to Conception

The geographic nonstationarity in US seasonal birth rates is more clearly presented in Figure 31, which employs spatial empirical Bayes smoothing to show patterns of seasonal birth rates lagged to estimated conception month for the nine-year period January 1979 to December 1987. The displayed values are the smoothed seasonal rates calculated by dividing the raw seasonal number of births (adjusted by seasonal length) within the climate division by the total number of births within the climate division. Lower values (blue) show a reduced fertility compared to other climate divisions.

Calculating the seasonal preference for conception of boys within each climate division is more complicated, because the raw numbers for male births correlate to the overall birth rates. To remove this effect, I used the formula

$$M_i = SR_i * B/4$$

where *i* is the season, *M* is the adjusted number of males for the season, *SR* is the sex ratio at conception and *B* is the total number of births for the climate division. Figure 32 shows the rate derived by dividing the birth rate adjusted number of raw males (*M*) in the season by the total number of males born in the climate division. Similar to the birth rate map, this map shows seasonal conception preference for males within each climate division. The seasonal differences in sex ratio at conception without adjustment for seasonal fertility are shown in Figure 33, which simply shows the smoothed rate derived by dividing the number of males conceived within each climate division in each season by the total number of births within that season. Lower values (blue) in this map show lower sex ratios compared to other climate divisions during each season of birth. For consideration of how these seasonal sex ratio and fertility patterns relate to climate variables, maps of temperature (Figure 34) and precipitation (Figure 35) are also presented.

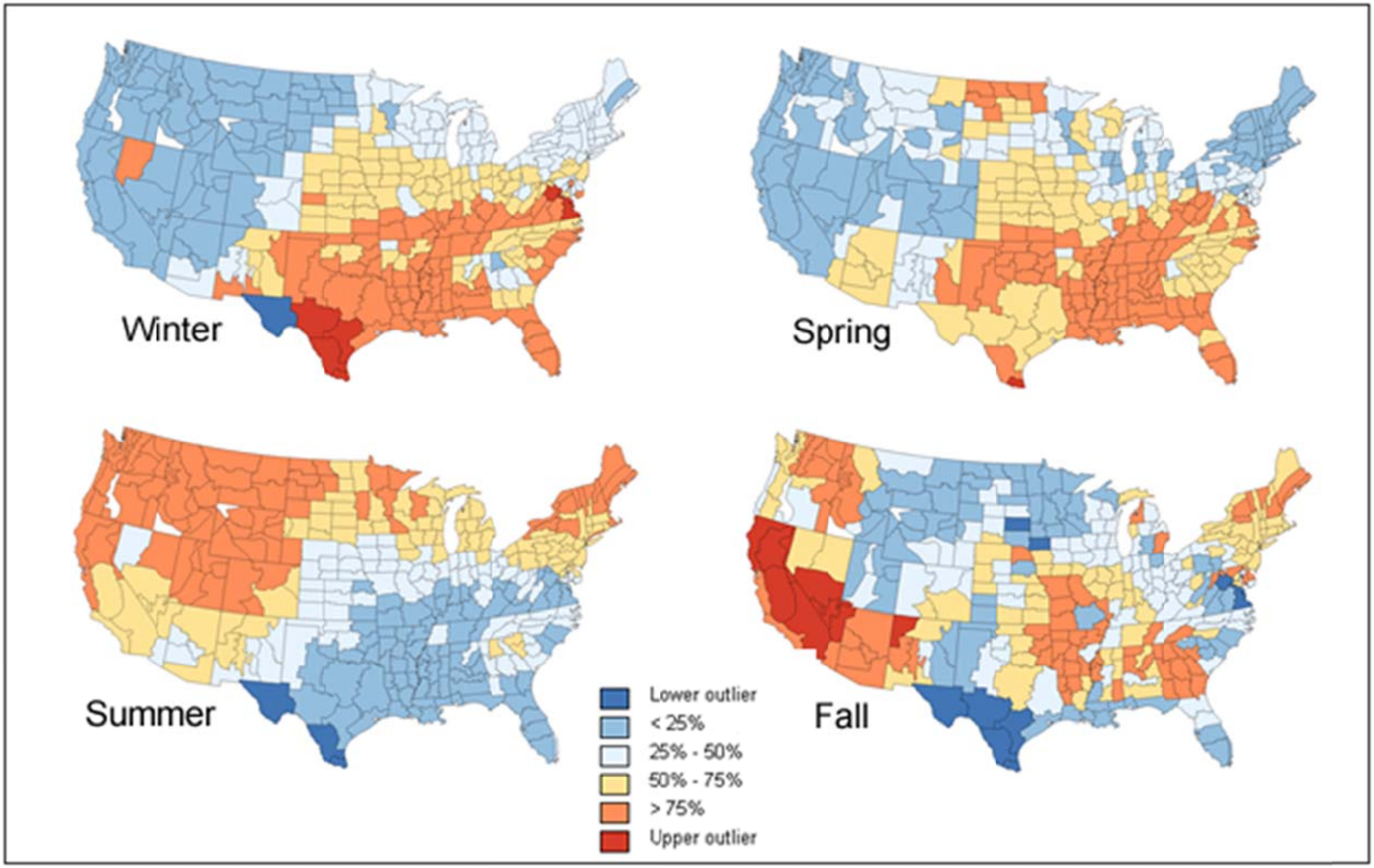


Figure 31. Smoothed birth rate lagged to conception season, non-Hispanic white births conceived 1979 to 1987. Spatial empirical Bays smoothing method, box map-hinge = 1.5, threshold distance weighting).

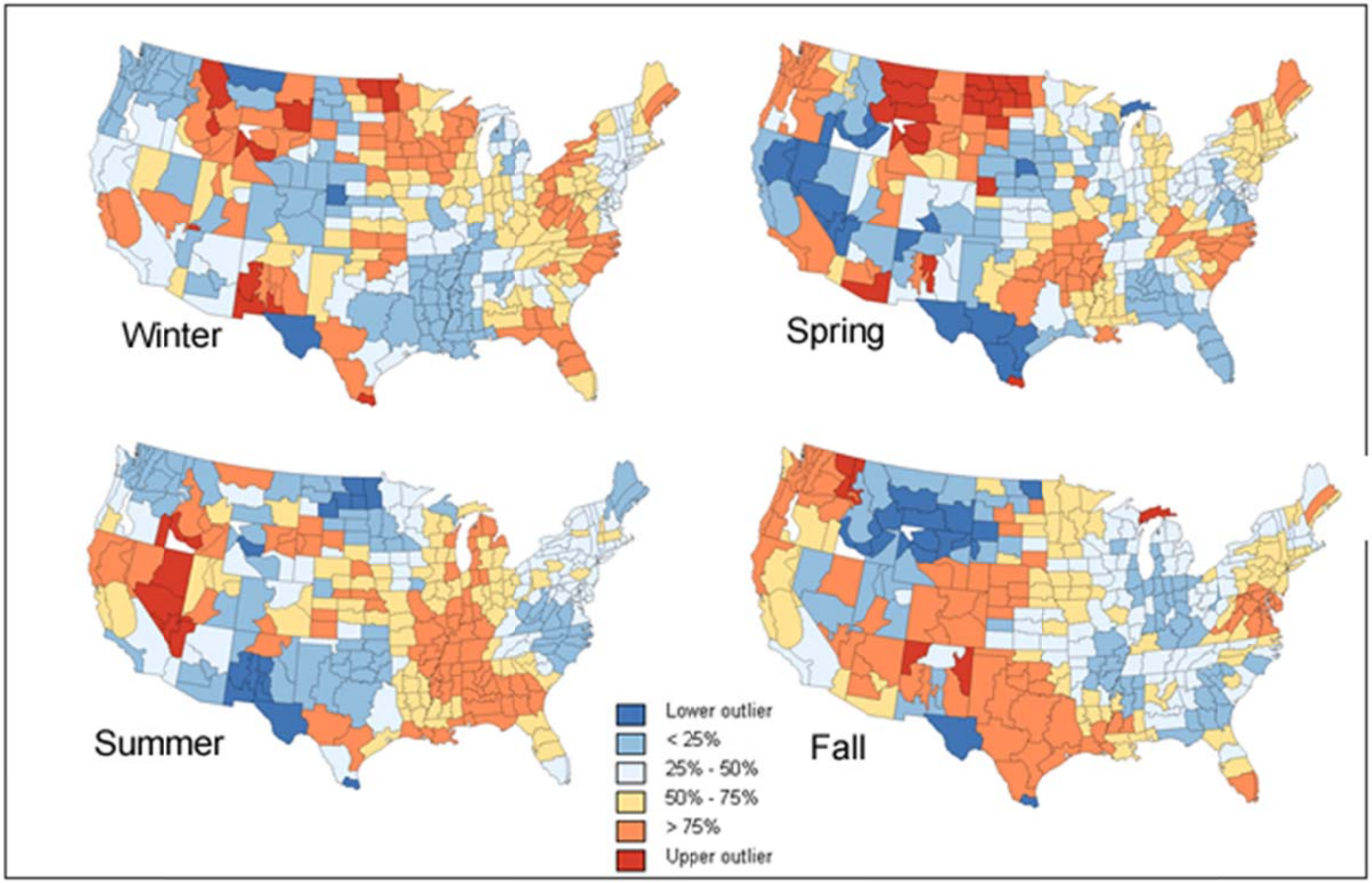


Figure 32. Smoothed rate for male births (adjusted male births by season/annual male births) lagged to conception season , non-Hispanic white births conceived 1979 to 1987. Spatial empirical Bays smoothing method, box map-hinge = 1.5, threshold distance weighting).

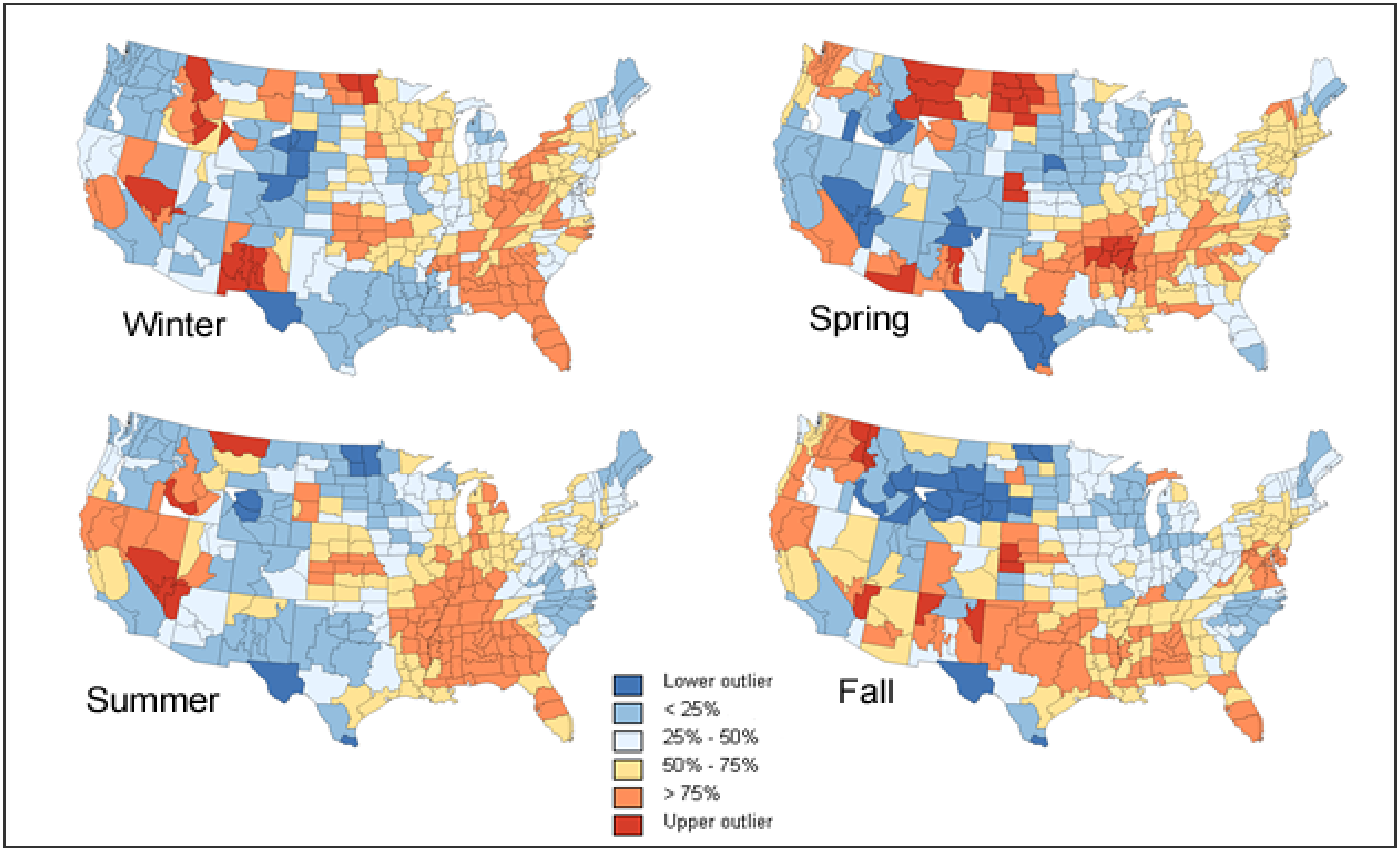


Figure 33. Smoothed sex ratio at birth lagged to conception season, non-Hispanic white births conceived 1979 to 1987. Spatial empirical Bays smoothing method, box map-hinge = 1.5, threshold distance weighting).

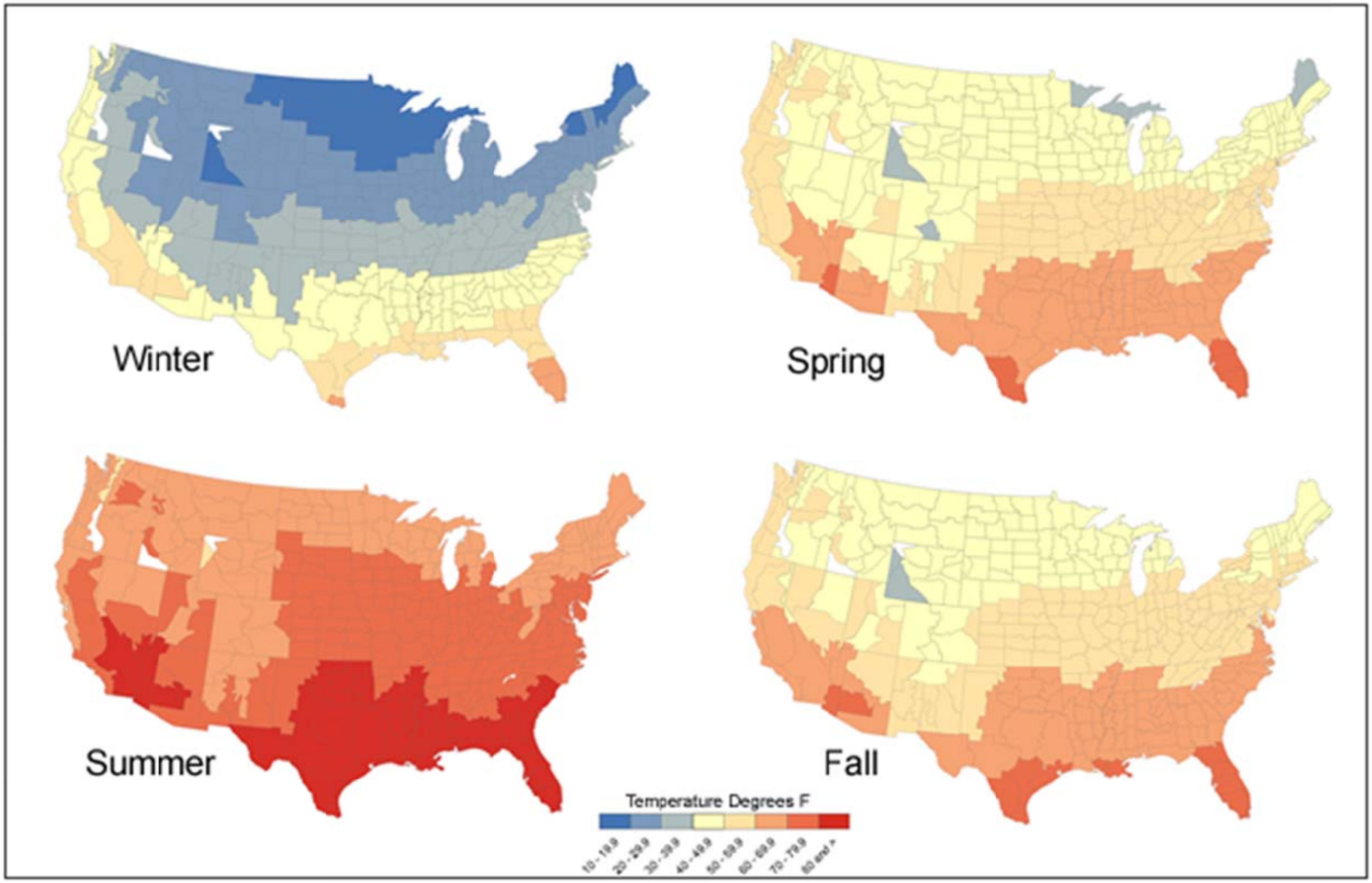


Figure 34. Average monthly climate division temperature (degrees Fahrenheit) by season, January 1979 to December 1987, excluding climate divisions not included in study area analysis.

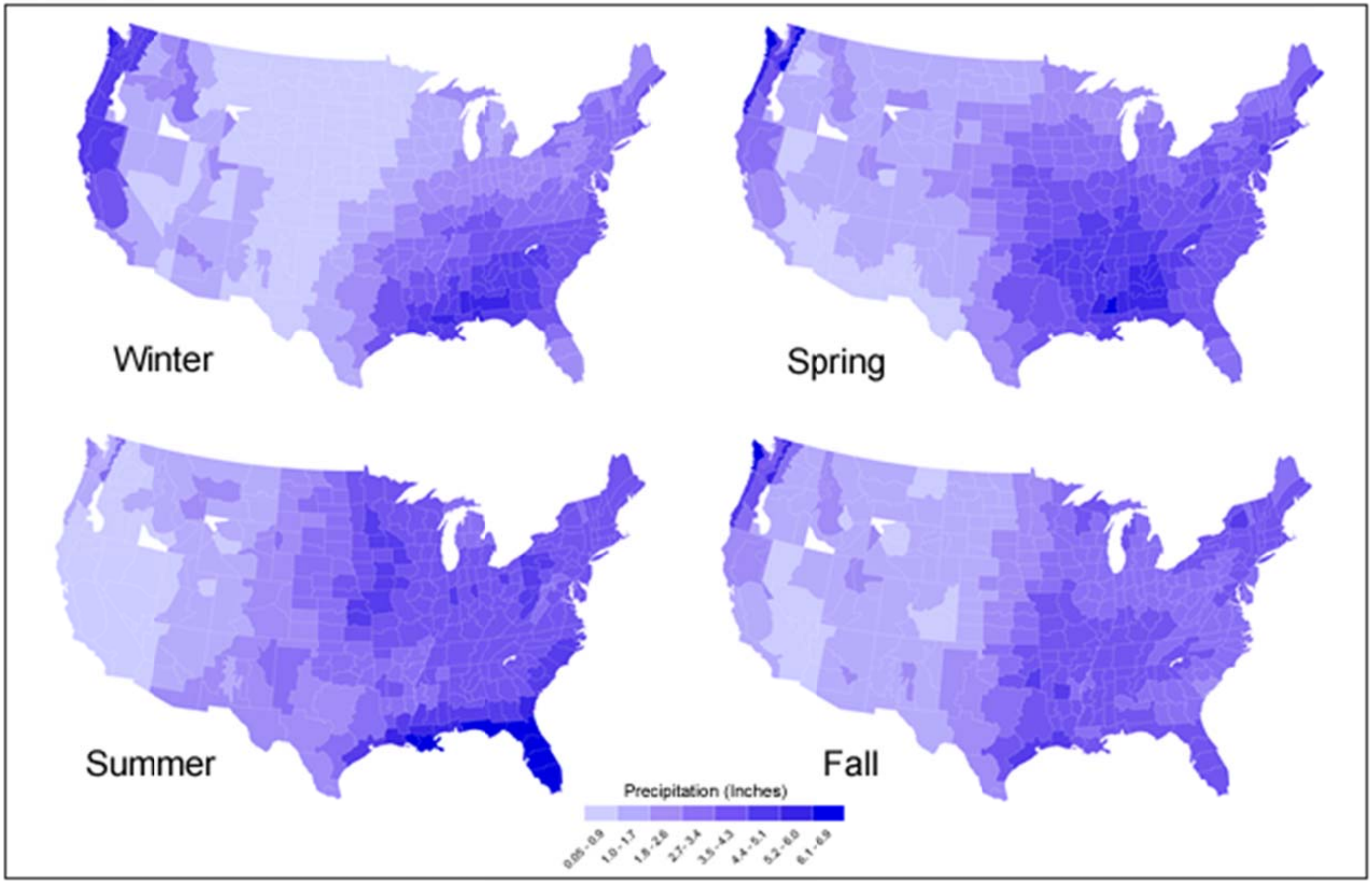


Figure 35. Average monthly climate division precipitation (inches) by season, January 1979 to December 1987, excluding climate divisions not included in study area analysis.

These figures show that geographic differences in seasonal birth conception rates are easily visualized, while sex ratio is less so. Most notably, maps of winter and summer birth rates in Figure 31 are virtually inverse, with the Southeast experiencing its highest seasonal rates in the winter and the lowest in the summer, while the opposite is true in northern latitudes and most of the west. The rates during spring are similar to that of summer, although the relatively higher rates of the upper Midwest during the spring may be due to suppressed fertility during the region's continental effect winters. Fall conception rates are the most complex geographically, with the extreme southwest and Florida remaining low but the upper Southeast returning to high rates, the Rocky Mountain west returning to low rates of the winter, but the Pacific states and the southwest retaining the higher rates of summer. These patterns show that increases in seasonal temperatures are associated with relative increases in fertility in higher latitudes, with local variation due to coastal or high elevation effects. Some of these results conform to those of Lam and Miron (1996) and Seiver (1985), who found that high temperatures in southern US states or extreme temperatures in any US state suppress conceptions.

Precipitation is somewhat correlated to temperature, in some regions more than others, but its variation across the US is more longitudinal than latitudinal. Some work has been done to evaluate the effect of seasonal monsoons on sex ratio and births rates (Kumari and Rao 1982, Sule and Madugu 2004); however, literature on this subject in temperate climates is scarce. In the Southeast, some of the highest rainfall values occur in the summer, as well as the highest temperatures of the year. Yet, this is the lowest season of fertility in that region. Temperature, and perhaps related humidity, may reach levels that depress rather than encourage fecundity.

Sex ratio at birth, lagged to seasonal conception periods, does not geographically plot with the elegant precision of conception rates. Broadly, more boys appear to be conceived in the fall in lower latitudes than during fall in higher latitudes (Figure 32). Sex ratio at conception also appears to display some geographic nonstationarity (Figure 33). There is a core high sex ratio zone in the southeast US compared to much of the west, which is similar to the persistent patterns of temperature and precipitation across seasons in the continental US. While conception sex ratios within broad latitudinal groupings (as in Figure 30) show a correlation of seasonal sex ratio with fertility rates in higher latitudes, this may be a function of factors operating within the high latitude cities of the Northeast.

With some evidence of geographic grouping by season, one would expect that spatial autocorrelation would be present in climate division sex ratios lagged by conception season. Temperature and precipitation are certainly spatially autocorrelated; indeed, they are the classic example of this. However, sex ratio at conception for non-Hispanic white births by climate division is not spatially autocorrelated when aggregated for the 1979–1988 study period (Table 9).

Despite the lack of spatial autocorrelation in sex ratio at conception rates in climate divisions, regional and seasonal changes in temperature, and possibly, precipitation, are associated with seasonal variation in sex ratio. A year-by year analysis of monthly conception sex ratio and birth rates during this period offers some additional insight into the seasonal nature of sex ratio and its relationship to fertility.

Table 9. Global Moran's Index values for sex ratio aggregated to estimated season of conception, January 1979 to December 1987, calculated using threshold distance of 294,177 meters.

Season	**Moran's Index**	**Expected Index**	**Variance**	**Z-score**	**P-value**
Winter SR	-0.007158	-0.002959	0.000538	-0.181043	0.856334
Spring SR	0.008611	-0.002959	0.000543	0.496685	0.619411
Summer SR	0.009997	-0.002959	0.000544	0.555517	0.578541
Fall SR	-0.006679	-0.002959	0.000539	-0.160179	0.872740

Monthly and Annual Variation in Birth Rate and SRB Lagged to Conception

Values for sex ratio at birth lagged to the month of conception for the 1979–1988 period are highly variable compared to estimated conception rates, but a consistent pattern can be discerned in both (Figure 36). There is a strong circannual pattern to estimated conception rates, more apparent when a three-month moving average is applied. A single late-year peak occurs in each year.

Although not apparent in a plot of month by month variation, sex ratio has a similar but less coherent circannual pattern discernible in the three-month moving average. Again, sex ratio appears to be "in phase" with birth rate in general, as asserted by Cagnacci et al. (2003), but important differences can be seen. The sex ratio at conception annual wave is roughly synchronous to the conception wave in its low points, but peaks vary in timing from year to year and are often bimodal. The double-humped pattern described by Jongbloet et al. (1996) can be seen in some years and the peak of male conception precedes the peak of birth rate in each year except 1986, when both coincide. Some quantification of these patterns is available in time series analysis.

The circannual pattern of birth ratio variation is obvious from visual observation and can be measured using the SAS Time Series Forecasting System, which attempts to fit time interval data to a number of common time series models after assessing trend, serial autocorrelation, and seasonality. Because the time series of birth rates during this period have no detectable upward or downward trend (Dickey Mann Test, $p=<0.0001$), but do display seasonality (seasonal root test, $p<0.0001$), it fits well to a seasonal exponential smoothing model (Figure 37). Unlike the moving average trend displayed on Figure 36, each observation in the series is not assigned an equal weight; instead, exponentially decreasing weights are assigned over time. For the time series y_t of monthly conception rates, the seasonal exponential model is:

$$y_t = \mu_t + S_{t,p} + a_t$$

where μ_t represents the time-varying mean (level) term, S represents the time-varying seasonal term for the p ($p = 1,2,\ldots,$) seasons in the year, and a is a white noise error term. At each time period t, the time varying components are estimated by smoothing equations.

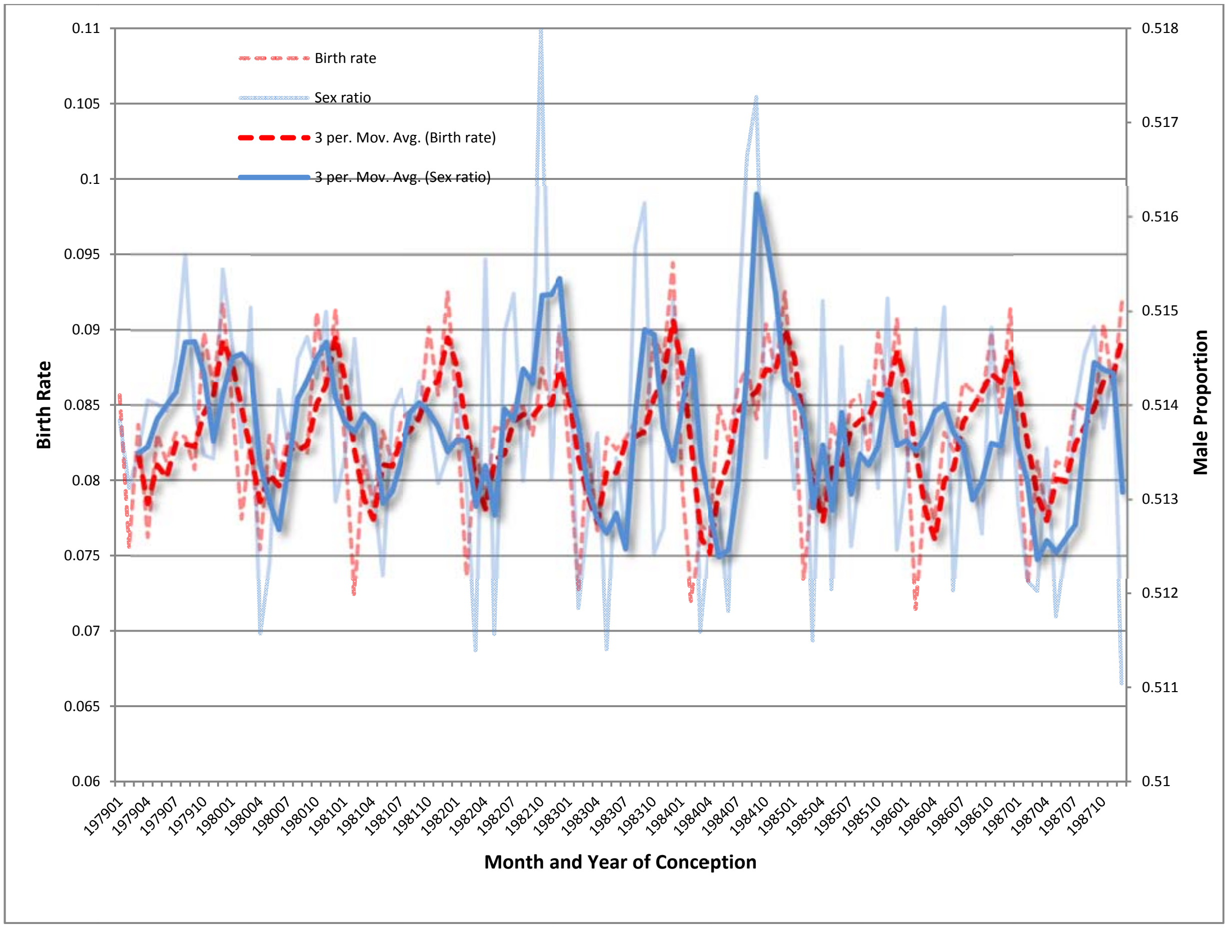


Figure 36. Monthly conception and lagged sex ratio rates by month for births to non-Hispanic mothers, Jan. 1979–Dec. 1987, with three month moving averages.

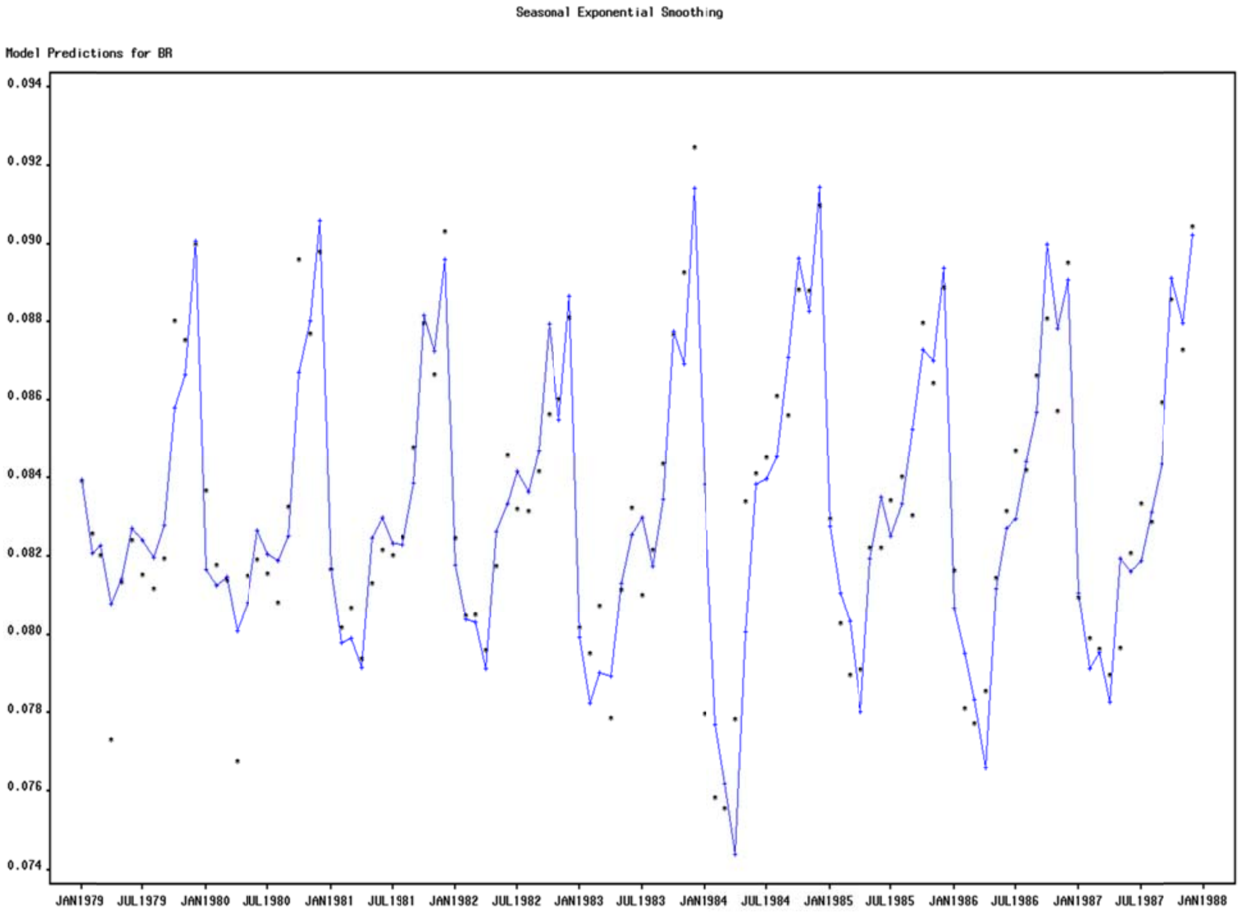


Figure 37. Seasonal exponential smoothing of lagged monthly birth rates based on annual birth totals ($R^2 = 0.868$, root mean square error=.001336, non-Hispanic white births, January 1979 to December 1987).

The seasonal exponential smoothing model was selected by the automatic model selection feature of the SAS time series forecasting system as best fit for the 1979–1988 monthly conception values (R^2 =0.864) using root mean square error (RMSE) as the goodness-of-fit selection criterion. The model diagnostics for this series are acceptable for autocorrelation, partial autocorrelation, and inverse autocorrelation tests and pass white noise significance tests (Fisher's Kappa = 15.5, p<0.0001, Bartlett's Kolmogorov-Smirnov = .0.19, p<0.0001). This model has very good predictive power given that no adjustments for age or other demographic factors are included, except the restriction to non-Hispanic white mothers.

A similar model can be fit for non-Hispanic white birth sex ratio lagged to conception month, but does not pass white noise significance tests. However, the seasonal periodicity of sex ratio lagged to conception during this time period can be confirmed using the spectral analysis method of SAS software (PROC SPECTRA). I constructed a periodogram of the sex ratio lagged to the month of conception for non-Hispanic white births for each of the monthly periods from January 1979 to December 1987. The procedure makes trigonometric estimates of the frequencies, amplitudes and phases within the 108 monthly observations of this time series. It is a modification of Fourier analysis that allows an entire frequency band to be analyzed as a whole and the amount of variation for each of all possible cycles calculated. Spectral analysis is the process of cycle aggregation. The periodogram is smoothed by a weighted moving average to produce an estimate for the spectral density of the periodogram. A simple triangular weight was specified with the statement (weights = 1 2 3 2 1); other kernels produced essentially the same results;

This analysis assumes temporal stationarity: constant mean and constant variance of observations in the time course. No trend is apparent in three-month moving average trendline of sex ratio presented above in Figure 36 and the Dickey-Fuller single mean test (p = <0.0001) allows rejection of the null hypothesis that the time series is nonstationary for lags up to five time periods.

The periodogram produced by this procedure (Figure 38) shows the cycle with the highest variation occurs at 12 months, a confirmation of seasonal variation; the second peak occurs at 3 months. This analyses does not pass diagnostics to reject the null hypothesis that the series is white noise (Fisher's Kappa; = 7.67, Bartlett's Kolmogorov-Smirnov Statistic = 0.08, p<0.81). One problem with this statistic is that it assumes a sinusoidal pattern in the series, and we can see a bimodal pattern to several of the years. The seasonal pattern of sex ratio at conception, however, is strong and compares to the birth rate spectral analysis for the same period presented in Figure 39, which also shows a peak for 12 month cycles.

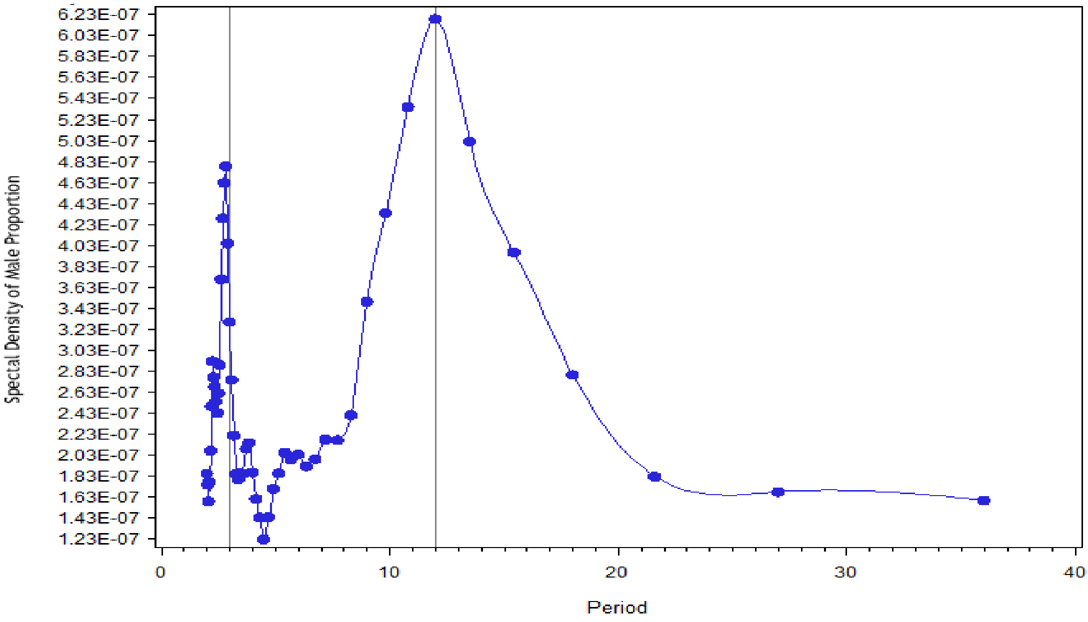


Figure 38. Plot of sex ratio spectral density estimate by number of monthly period for estimated month of conception, non-Hispanic white births, Jan 1979 to Dec. 1987. Vertical reference lines drawn at 12 and 3 months.

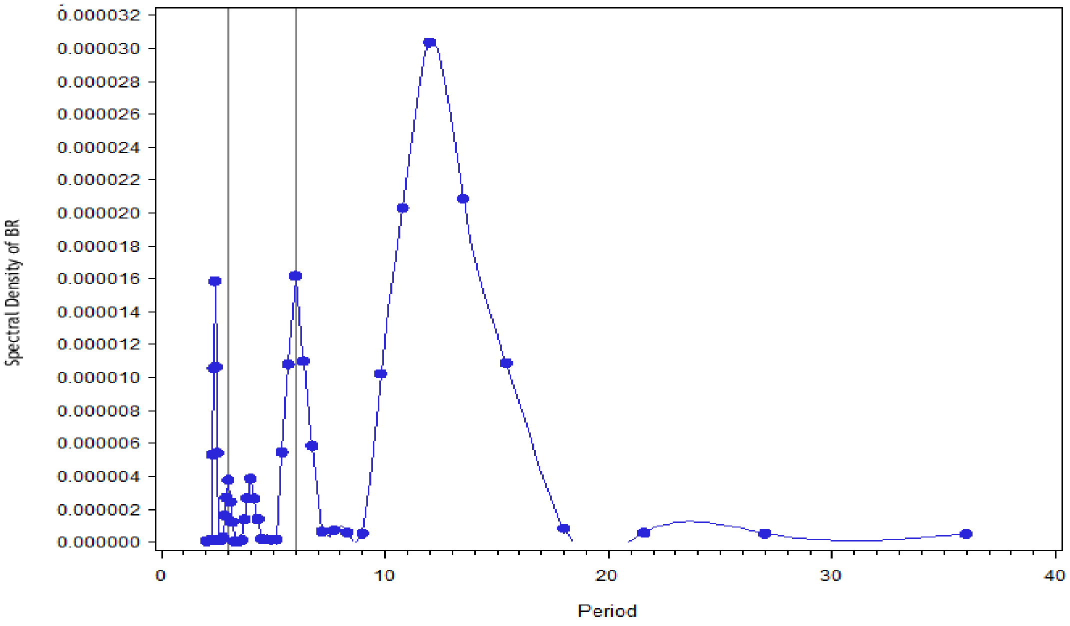


Figure 39. Plot of birth rate spectral density estimate by number of monthly periods for estimated conception month, non-Hispanic white births, Jan 1979 to Dec. 1987. Vertical reference lines drawn at 3 and 6 months.

Given these confirmations of annual variation of birth rate and SRB with seasonal periodicities, what covarying climate or other environmental conditions are most associated with this cycle? While month of conception sex ratio and birth rate both have apparent circannual rhythms, they are not significantly cross-correlated in their month-by-month variation, based on the SAS ARIMA procedure ($r_{pearson} = 0.113$, p = 0.71149). The most significant correlation between the two series occurs between sex ratio and one month lag of birth rate (r=0.26, p=0.008), reflecting the similarity of the timing of their troughs. The peak of sex ratio generally occurs before the peak of birth rate, similar to the aggregated monthly values for the entire study period presented at the beginning of this chapter. In several years, as mentioned above, the pattern is bimodal, with peaks before and after the peak month of conception.

The circannual rhythm of birth rate is not correlated to the average temperature in the month of conception ($r_{pearson} = .005$, p=0.606). However it is positively correlated to the temperature in the month *before* conception ($r_{pearson} = 0.401$, p<0001).

While this correlation is not high, the relationship is very consistent from year to year (Figure 40). This implies an association of seasonally rising temperatures with a possible hormonal response that increases likelihood of conception. The highest correlation occurs when birth rates reach their lowest annual value — this is when temperatures in the preceding month (B_TMP) are also lowest. The association is weakest between the cold month of December and the annual peak of birth rate. This stable pattern may illustrate a blending of cultural and biological influences, a largely biometerologic rhythm moderated by what is often termed "the Christmas effect": the higher coital frequency of the Christmas season superseding the possible seasonal hormonal decline when temperatures are low. There is also a subtle but noteworthy change to the pattern over the study period. There is an anomalously high peak of conceptions in December 1983 and thereafter summer conception rates are higher relative to the rest of the year.

Correlation between birth rate and photoperiod is present but less convincing than are temperature associations. Conception rate birth rate is not correlated to the length of day in the month before conception ($r_{pearson}$ =0.114, p=0.239) but is correlated to the length of day during

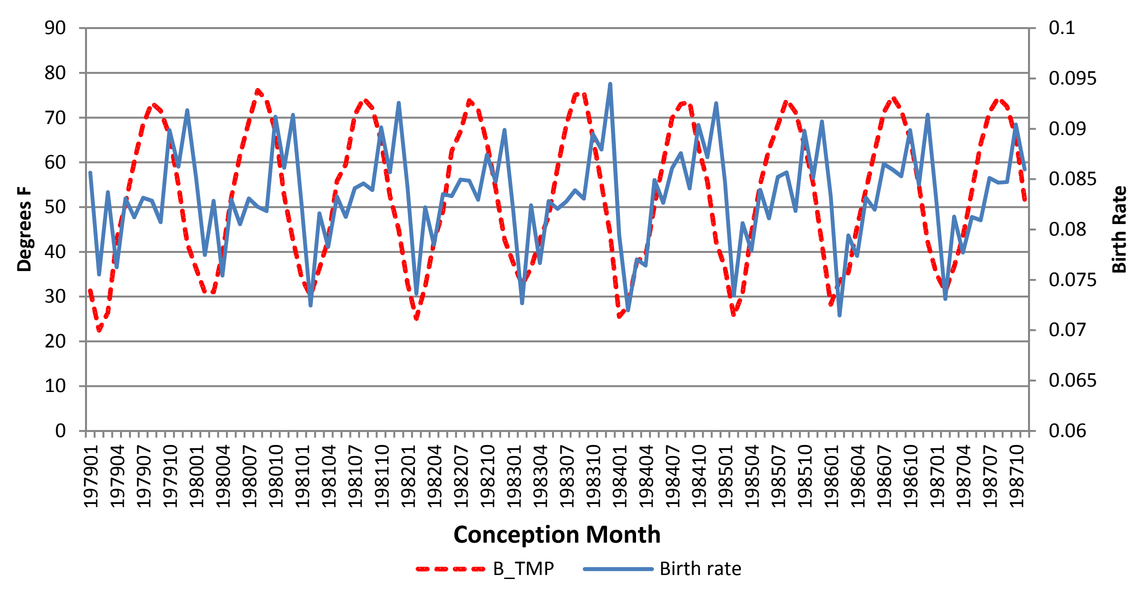


Figure 40. Birth rate estimated at month of conception and mean climate division temperature in month before conception, non-Hispanic white births, January 1979 to December 1987.

the same month ($r_{pearson}$ = 0.231, p=0.016), to a lesser degree than it is to the preceding month's temperature. In a month by month comparison, sex ratio at month of conception is not significantly correlated to daylength before ($r_{pearson}$=0.125, p=0.18) or during ($r_{pearson}$ =-0.056, p =0.54) the month of conception, nor to the temperature during the month of conception ($r_{pearson}$ =0.103, p = 0.287). It is, however, positively correlated to the temperature in the month before conception ($r_{pearson}$ =0.272, p=0.004). This agrees with Cagnacci et al. (2003), who found that sex ratio increased in Modena County, Italy with the increase in air temperature in the month before conception, and with Lerchl (1999), who found that increases in environmental temperatures prior to conception increased the probability of a male birth. It is also conforms to the speculation by Grech et al. (2002) that increased ambient temperatures were responsible for the latitudinal gradients of SRB among European nations. However, a stronger case for this relationship needs to be made for US births, particularly since photoperiod is also associated with sex ratio variation.

Associations of Sex Ratio at Conception, Daylength, and Temperature

Monthly Photoperiod Variation and Sex Ratio at Conception by Latitude

Although the correlations and regressions I have reported above point primarily to temperature as the environmental condition most associated with sex ratio variation, temperature and daylight are highly correlated (although lagged by one or two months), and daylength is a significant explanatory variable for sex ratio variation independent of temperature.

Navara (2009) speculated that the global latitudinal variation she found in sex ratio at birth was related to an interplay of temperature and daylength. Higher SRBs were found in higher latitudes, which had lower ambient temperatures but greater variation in daylength. Photoperiod, the length of day between sunrise and sunset, is a reliable cue used by both plants and animals to anticipate seasonal changes and make adjustments to physiology and behavior (Bartness et al. 1993). It is noise free, consistent from year to year, and reproducible in laboratory experiments. Although the reproductive mechanisms in mammals that are triggered by changes in photoperiod are not worked out, Roenneberg and Aschoff (1990b) hypothesized that photoperiod was an environmental signal to which human conception rates also responded.

They did not find, however, strong evidence of this effect in the current birth rates of the US and other industrial countries.

I am not aware of any study of the association between photoperiod at the time of conception and sex ratio at birth in US births. Roenneberg and Aschoff (1990b) found that high conception rates in higher latitudes were associated with a photoperiod of 11 to 13 hours, which corresponds to daylengths during and near the vernal and autumnal equinoxes in the US. If there is a latitudinal and seasonal component to US sex ratios, the nature of its interaction with daylength is a reasonable association to explore, since this factor varies precisely as a function of latitude and time of year. For the births to all non-Hispanic mothers conceived between 1979 and 1987, the highest sex ratio occurs at a daylength of approximately 12 hours (Figure 41). I derived this value by converting the monthly daylength average to its integer value to create eight daylength categories ranging from 8 to 15 hours (using these categories, only births in the high latitude zone occur at 8 or 15 hours).

However the difference between sex ratio at conception among these categories is not significant ($\chi^2 = 4.23$. $p=0.101$). When segregated by high and low latitude zones, conception month sex ratio is highest again in months averaging 12 hours of daylength for both zones, but again not significantly (high: $\chi^2 =7.5502$, $p=0.37$; low: $\chi^2 =4.0296$, $p=0.5452$).

Both the range and amplitude of sex ratio variation by daylength is greater in the high latitude zone (Figure 42). In high latitudes, 12-hour day lengths in the high latitudes occur both during the cool spring and the warm fall, on the either side of a daylength peak during the summer solstice. Also displayed in Figure 42 is the average temperature in the month before conception for each daylength range, a value which may combine both warm fall and cool spring temperatures.

In high latitudes, the sex ratio at birth is highest during fall months approximately 12-hour days, which follow the warmest month of the year. As days grow longer, sex ratio decreases in this latitude zone. In lower latitudes, the peak day length conception value is also twelve hours, but temperatures in the eleven hour category do not dip as they do in high latitudes.

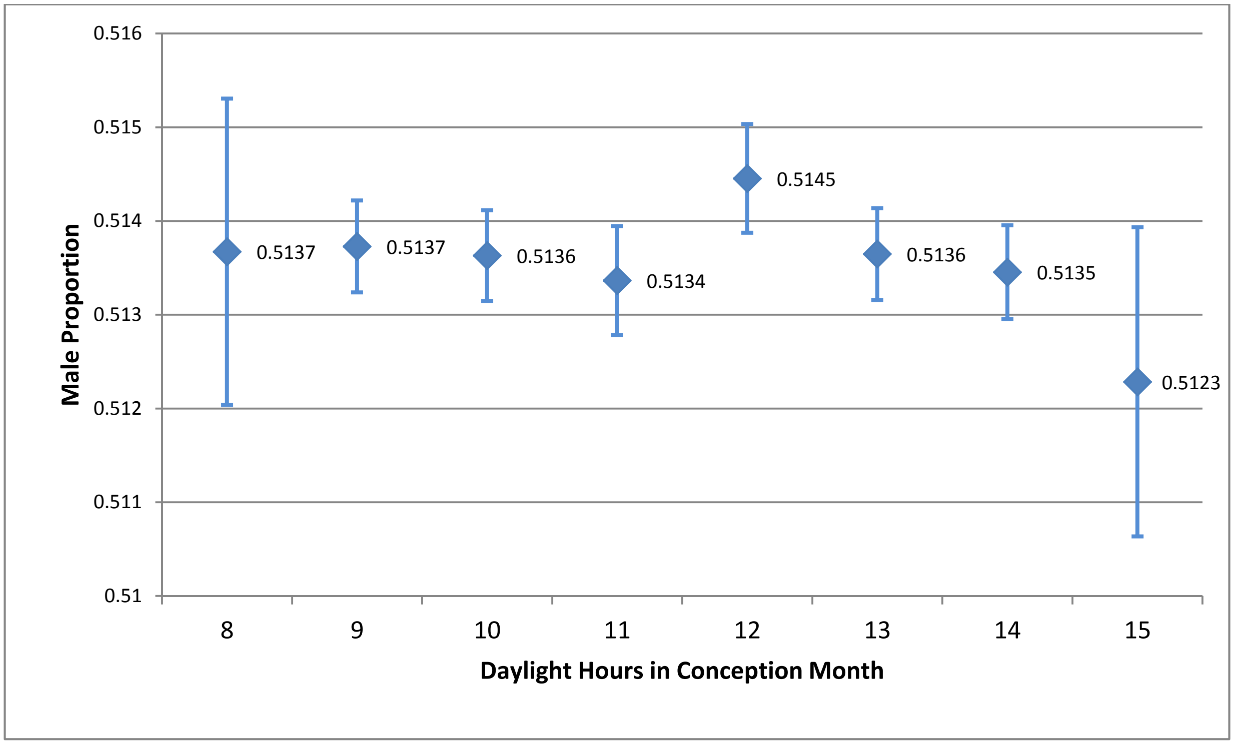


Figure 41. Sex ratio at conception with confidence intervals, by number of hours of daylight in conception month, rounded to nearest integer, non-Hispanic white mothers**.**

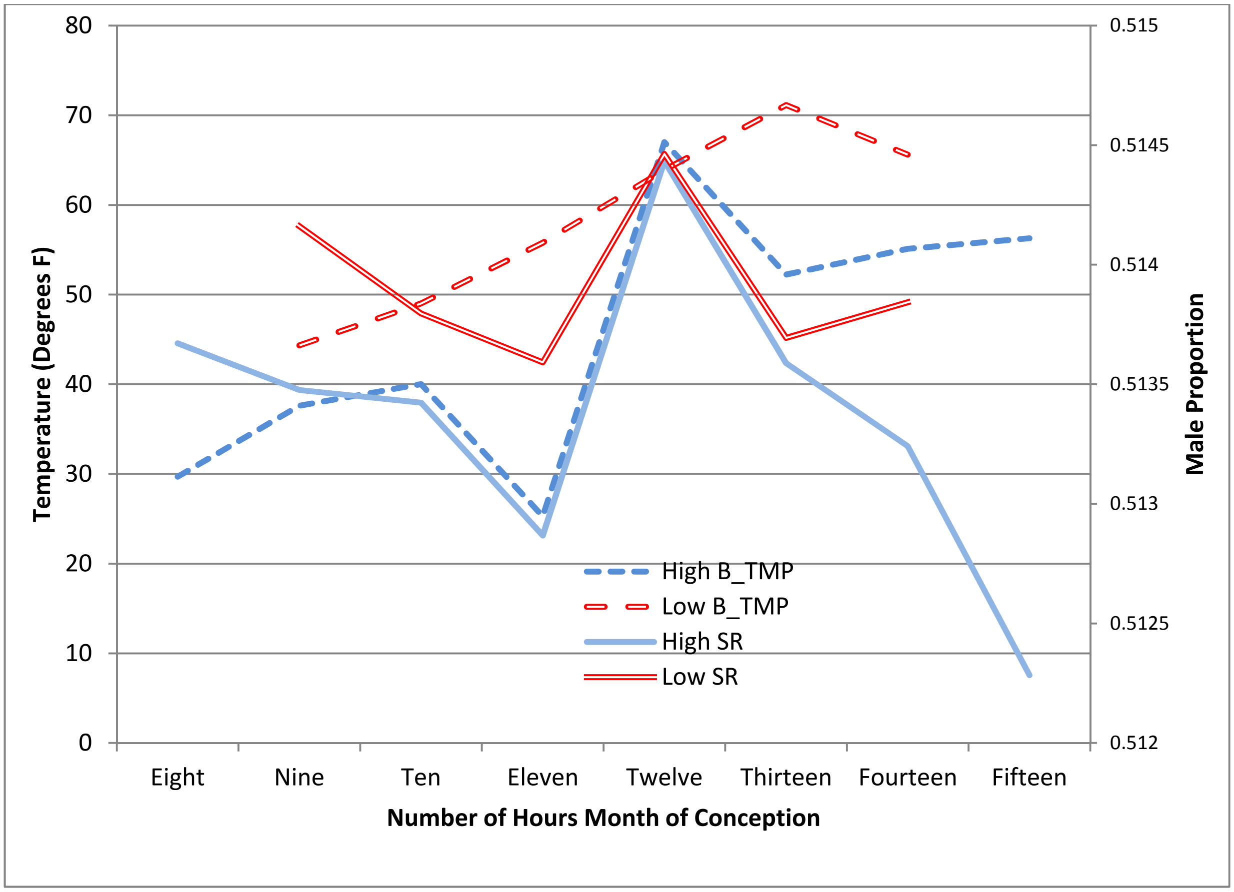


Figure 42. Conception month sex ratio and temperature in month before conception by latitude zone and number of hours day light during month of conception, Jan 1979– Dec 1987 non-Hispanic white births.

If photoperiod has some influence on sex ratio, it might act in concert with ambient temperature or some other latitudinal signal that daylight is increasing in length towards better resource conditions or decreasing towards unfavorable ones. The relationship between sex ratio, daylength, and temperature is not explained by the above comparison, but it serves to illustrate the influence of daylength and temperature on sex ratio, if it exists, operates differently as latitude changes. Variation in monthly temperature appears to be more closely associated with seasonal changes in sex ratio than does variation in photoperiod.

Sex Ratio at Conception and Temperature

When all non-Hispanic white births for the period are aggregated, significantly more non-Hispanic white males are born when the previous month's temperatures are 70 degrees F or higher (Figure 43; χ^2 =22.88, p =0.0004). This relationship is not linear, however, as the sex ratio conceived when the previous month's temperatures are lower than 70 degrees are not significantly different.

I also considered deviation from mean temperatures for this subpopulation (Figure 44), using z-scores calculated using the 1971–2000 mean monthly temperature for each climate division. Values for the month before, during, and after estimated conception date were evaluated to see if extreme temperatures at or near the time of conception are significantly associated with variation in the rate of males conceived by i non-Hispanic white mothers during this period. Although sex ratio is higher when temperatures are above the mean (z-score greater than 0), or above one standard deviation (z-score greater than 1), these differences are not significant. Sex ratio is also higher when temperature is two standard deviations or more above the average before or after the month of conception, but also non-significantly. The exception is that temperature two standard deviations below normal results in a higher number of male births during the month of conception than for any other z-score class.

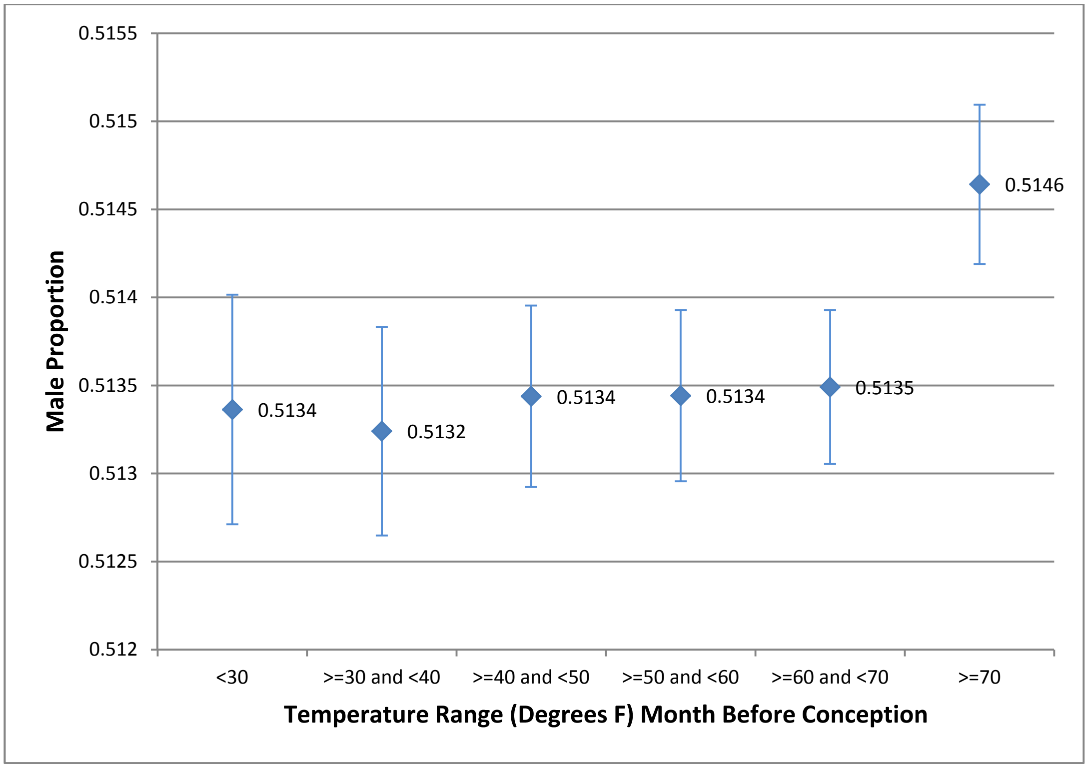
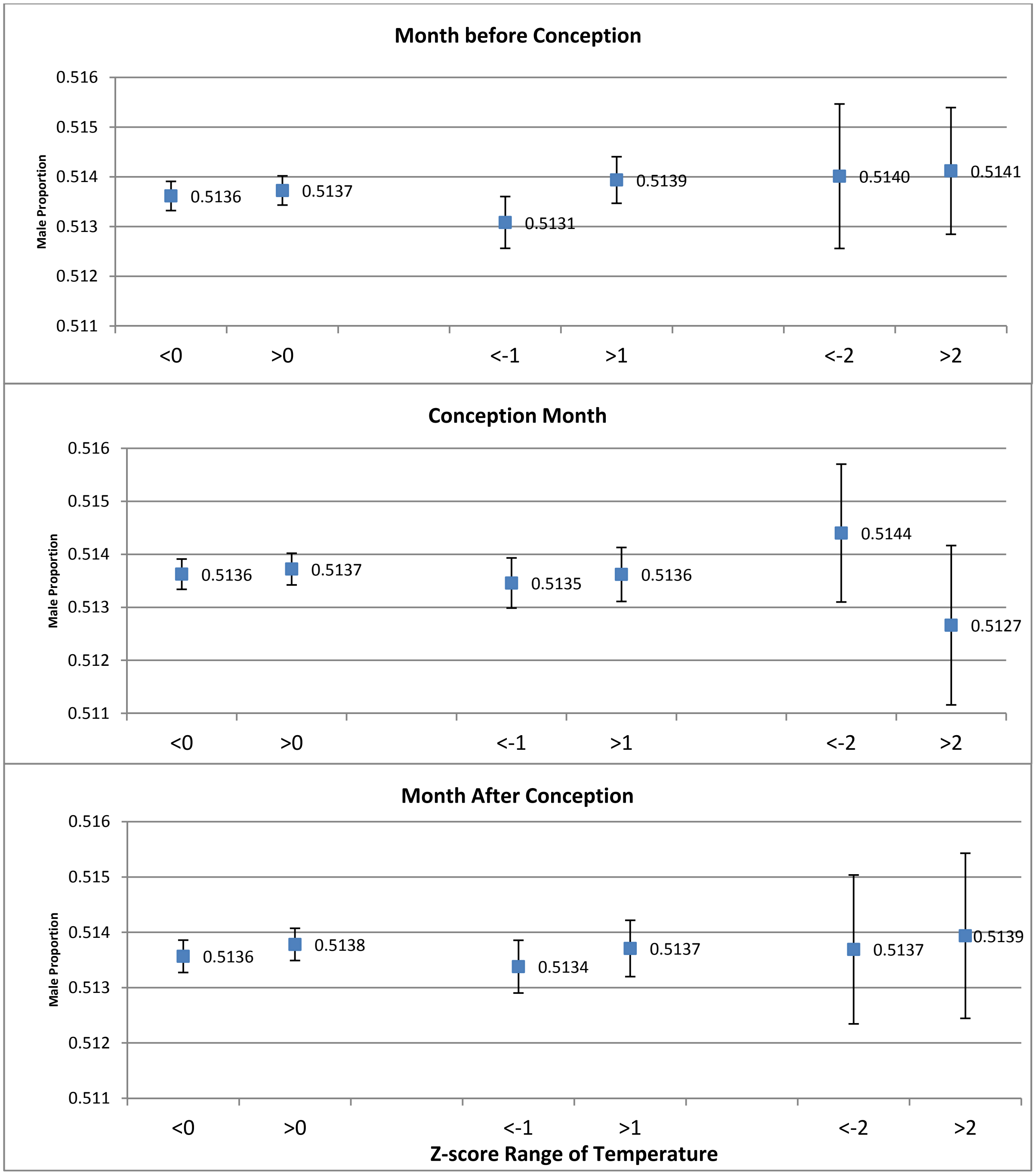


Figure 43. Sex ratio by temperature in month before conception, non-Hispanic white mothers, Jan 1979–Dec. 1987. Confidence intervals are shown by vertical bars.



Month before Conception

Conception Month

Month After Conception

Figure 44. Lagged sex ratio by standard deviation from average monthly temperatures in month before conception, month of conception, and month after conception based z-scores calculated using 1971–2000 average temperature, all non-Hispanic white births, Jan 1979–Dec 1987.

Global Model of Sex Ratio at Conception with Climate, Socioeconomic and Individual Biological Factors

The exploratory results I have presented above provide strong evidence of seasonality and geographic nonstationarity of the sex ratio at birth during the period 1978–1988, which could possibly be attributed to factors associated with climatic variation. However, social and demographic factors that may be associated with sex ratio at birth may also vary geographically and seasonally across the US, possibly covarying with climate variables. The association of low precipitation climate variations with Hispanic populations I discovered early in this analysis is an example of the potential confounding that might arise when trying to isolate climate as an explanatory factor in the complex biological equation that SRB entails. The logistic regression method is particularly well suited to this task, as it is able to model both categorical and continuous variables on a dichotomous dependent variable. To explore the association of climate variables and SRB, I attempted to fit two logistic regression models. The first examines the explanatory value of climate variables at the estimated time of conception in concert with a number of individual biological and social variables for all births during the 1979–1988 study period. The second uses a similar model to examine only white non-Hispanic births, to which a number of geographic and county social and economic variables are added.

Independent biological and cultural variables initially considered in the models include mother's age, mother's race and ethnic origin, birth order of the child, and number of gestation weeks of the birth. SRB varies significantly by preterm, term, and postterm categories but gestation length is not, of course, a condition present at time of conception. It is an outcome of a complex set of interrelated socioeconomic, demographic and behavioral factors, some of which, like smoking and maternal stress, have been implicated in SRB bias. As such, it is included as a general proxy of these conditions in the parents at the time of conception. As another proxy for socio-economic status of the parents, I included educational status of the mother. No data related to the father was included due to the large number of missing records for paternal information. I coded all these selected variables into classes as described in Table 10, which shows total observations for each variable, the number of missing values, and which variables were selected as reference variables for classes.

Table 10. Independent variable categories for logistic regression model, all births 1979–1988 birth data. Observations total 35,142,111 for each variable.

Variable	Category Code	Description	Number
Age of mother	1	<18 years	1796803
	2	18 to 30 years	26745121
	3	31–39 years	6323864
	4	Over 40 years	276323
Birth order	1	First born	14696670
	2	Second born	11433206
	3	Third or greater	8817615
	Null	Missing	194620
Gestation weeks	1	>=37 and <42	26933390
	2	<37	3125541
	3	>=42	2362864
	Null	Missing	2720316
Race of mother	1	White	28311462
	2	Black	5537243
	0	Other	1182687
	Null	Missing	110719
Education of mother	1	Less than High school	5989633
	2	High school	11901022
	3	Some college	5391494
	4	Bachelor’s degree or higher	4425516
	Null	Missing	7434446
Origin of mother	0	Non-Hispanic	32046006
	1	Hispanic	3096105
Plurality of birth	1	Singleton	34411773
	2	Twins	714091
	3	Other multiple	16247
Marital status	1	Married	26733656
	2	Unmarried	7217170
	Null	Missing	1191285

For clarity of interpretation, I coded number of gestation weeks, mother age, and plurality, and birth order into classes rather than include them as continuous variables. In addition to these demographic and biological variables, all climate variables assembled for this study were also considered in logistic regression model building, described previously in Table 1. Unlike selected demographic and biological variables, climate variables are included as quantitative independent variables in the model. For each climate variable, three values for each birth record were calculated: the value in the month before the estimated conception month, the value during the conception month, and the value in the month after conception (e.g., B_TMP, TMP, A_TMP, to represent temperature before month of conception, temperature during month of conception, and temperature month after conception, respectively). The conception month is estimated using gestation weeks and the birth date (GW), as described in the methods section.

The “Allbirth” and the “Non-Hispanic White Birth” models were fit using the SAS LOGISTIC procedure, modeling the probability that birth would be a male and using the Fisher scoring method of estimating the regression parameters. Initial model runs used stepwise selection procedure to reduce the total number of variables, specifying a significance level of 0.10 for entry into the model and 0.05 for retention. Thereafter, selection with a significance level of 0.05 was used to fit the model, based on a chi-squared distribution of the likelihood ratio of each independent variable. In this method, global model goodness of fit is given by calculating negative two times the difference of the likelihood for the null model and the fitted model (-2 LOGL), a maximum likelihood test described by Hosmer and Lemeshow (1989). Models with the smallest significant p-values for this test were sought, along with model that had the lowest Akaike Information Criterion (AIC) and Schwartz Criteria (SC), which evaluate each model by the number of independent variables and number of observation. These criteria reward parsimony by penalizing for the number of predictors in the model. Finally, I selected models with non-significant values for the Hosmer-Lemeshow test, which tests the null hypothesis that this is no difference between the observed and predicted values of the dependent variable.

This dataset excludes Alaska and Hawaii due to lack of climate division data in those states; in the remaining states only births to which I could assign a conception month by lagging gestation weeks from birthdate are included, leaving a total dataset of 31,698,168 records. The resulting odds ratios and confidence limits for the best fit model are plotted in Figure 45; coefficients and other model parameters for each retained variable are shown in Table 11. The results of the Allbirth model for social and demographic variables are in line with the findings of most sex ratio studies. Odds ratios for male births are high for preterm and term births compared to the reference postterm category, in keeping with previous studies on SRB and gestation length. Also conforming to most studies on the relationship between plurality and SRB, singleton births have a higher sex ratio than do that of twins (triplets or higher as the reference variable). Firstborn children have a higher sex ratio than second born, with both higher than third born or higher (reference variable). Black births have a lower odds ratio for male births than does the "Other Race" category, which serves as the reference variable for this factor. The confidence interval for white births crosses the 1.0 odds ratio boundary, probably due to fact that the other race category includes subpopulations that report both higher and lower sex ratios at birth that do white births. Non-Hispanic white births are more male biased than Hispanic white births in this model, as they are reported to be in other studies (e.g., Branum et al. 2009).

Marital status, mother age, and maternal education were also significant in various runs of this model, although their contribution varied in association with other variables. Mother's age is a significant factor if parity is removed. These variables are logically collinear but do not exhibit high correlation values in this analysis. Mother's education can also be fit in this model, although the number of missing variables values for this value variable reduces the model's efficiency. When mother's age and maternal education level are included, the importance of parity decreases. These three variables were thus excluded from the final model for parsimony and because they did not affect the significance of climate variables.

The temperature in the month before conception (B_TMP) was consistently significant in all model fit exercises and is the only climate variable to survive rigorous model fitting. Since it is evaluated as a continuous variable, its relative change in the odd ratios appears small: for each 1 degree increase in temperature in the month before conception, there is a 0.000084 increase in the likelihood of a male birth.

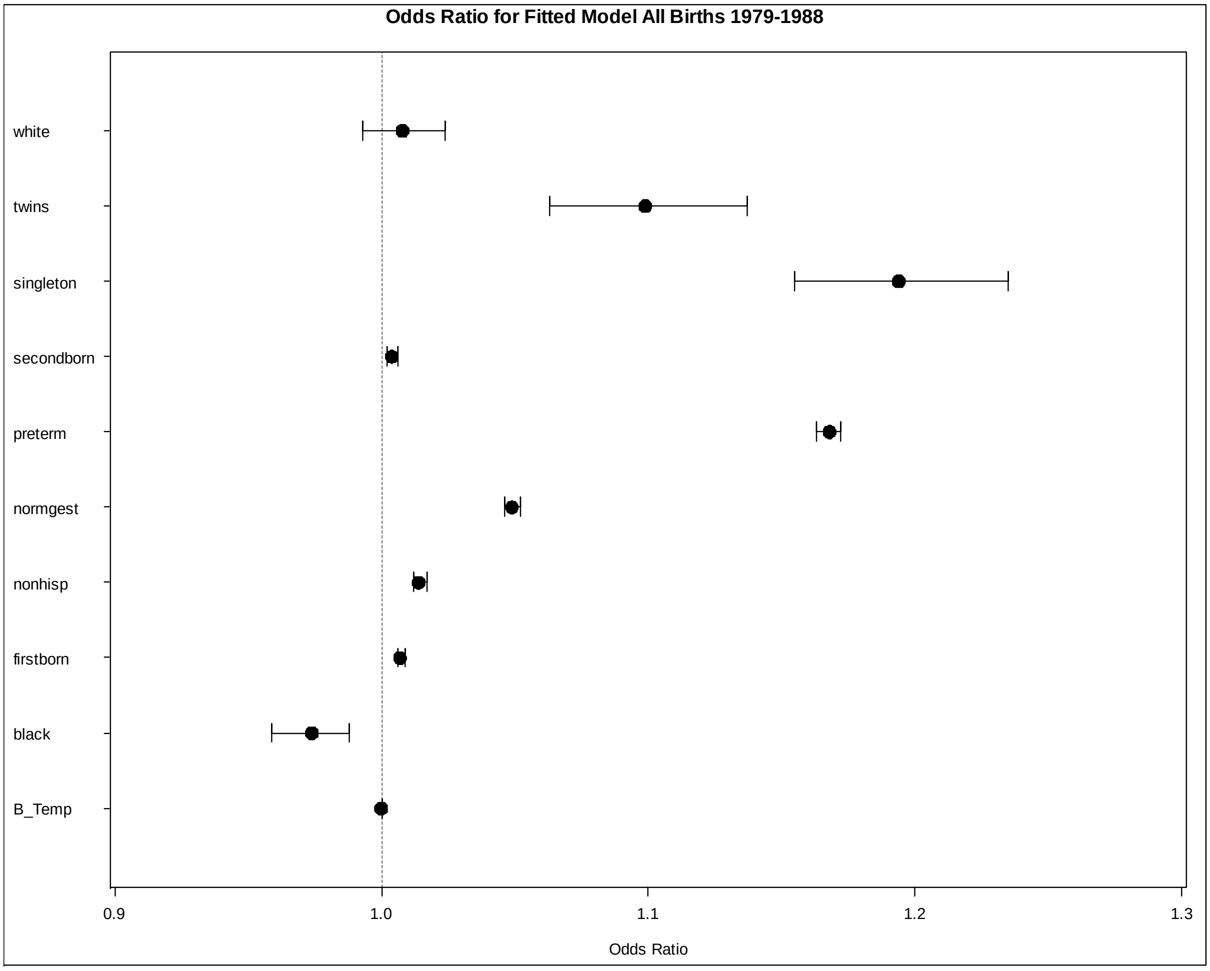


Figure 45. Plot of odds ratio of parameters for fitted logistic regression model of all births for 1979–1988 study period, odds ratio and confidence range of male birth displayed.

Table 11. Maximum likelihood estimates of parameters for fitted model of all parameters for all births during 1979–1988 study period with likelihood of male child as the model estimated.

Parameter	DF	Estimate	Std. Error	Wald Chi-Square	Pr > ChiSq
Intercept	1	-0.0422	0.00646	42.5506	<.0001
B_TMP	1	0.000084	0.000022	15.1694	<.0001
Parity (Firstborn)	1	0.00372	0.000492	56.971	<.0001
Parity (Secondborn)	1	0.000038	0.000521	0.0054	0.9415
Motherrace(White)	1	0.0144	0.00261	30.6332	<.0001
Motherrace(Black)	1	-0.0207	0.00266	60.501	<.0001
Gestation (Normal)	1	-0.0199	0.000656	924.9925	<.0001
Gestation (PreTerm)	1	0.0874	0.000929	8862.2765	<.0001
Nonhispanic	1	0.00701	0.000639	120.0728	<.0001
Plurality (Singleton)	1	0.0867	0.00577	225.6744	<.0001
Plurality (Twins)	1	0.00396	0.00594	0.4444	0.505

The global test statistic (-2 LOG L test) for the Allbirth model is significant (p<0.0001). However, the Hosmer Lemeshow goodness of fit test (SAS *lackfit* parameter) is also significant (χ^2 = 124.2, p<0.0001), which indicates an inadequate model because the difference in predicted and observed values of the response variable are not significant. While this model supports a hypothesis that temperature is a significant factor in the US sex ratio at birth, it suffers from some specification deficiencies. The explanatory variables do not include any geographic subdivisions that might covary with temperature or other climate variables. I am also concerned that the post and preterm gender effects may exist in the months that begin and end the 10 year study period**,** giving excessive weights to the climate variables in the season these trailing effect months occur.

To address these concerns and examine sex ratio at birth in the context of socioeconomic variation, I created another model using only births to non-Hispanic white mothers conceived between January 1979 and December 1987, based on the gestation weeks (GW) estimation method. Individual level variables described above, excluding race of mother and Hispanic origin of mother, were again included. To consider local socioeconomic associations, I joined the County FIPs code of each birth record to selected income and health county level variables derived from US Census and US Bureau of Economic Analysis data and compiled in US City and County level data books (Table 12).

Table 12. County level socioeconomic variables used in non-Hispanic white birth logistic regression model, 1979–1987.

Variable	**Description**	**Source**
PERPOV79	Percentage derived from Persons Living Below Poverty Line 1989 divided by total county population 1980	US Census, in 1983 County and City County Data Book
PERPOV89	Percentage derived from Persons Living Below Poverty Line 1979 divided by total county population 1990.	US Census, in 1994 County and City Data Book
PERCAPINC79	Dollars of Per Capita Money Income 1979	US Census, in 1983 County and City Data Book.
PERCAPINC85	Dollars of Per Capita Money Income 1985	US Census, in 1988 County and City Data Book
MEDHHINC79	Dollars of Median Household Income 1979	US Bureau of Economic Analysis, in 1983 County and City Book
IMR84	Deaths of Infants Under One Year 1988 Rate per 1000 Births	National Center for Health Statistics, in 1988 County and City Data Book.
IMR88	Deaths of Infants Under One Year 1988 Rate per 1000 Births.	National Center for Health Statistics, in 1994 County and City Data Book
UNEMPRATE80	Civilian Labor Force Unemployment Rate 1986	Bureau of Labor Statistics, in 1983 County and City Data Book.
UNEMPRATE86	Civilian Labor Force Unemployment Rate 1986	Bureau of Labor Statistics, in 1988 County and City Data Book.
PHYRATE80	Number of Physicians per 100,000 Population, 1980	1983 County and City Data Book
PHYRATE85	Number of Physicians per 100,000 Population, 1985	1988 County and City Data Book

All climate variables considered in the Allbirths model were also considered in the non-Hispanic white births model. To better quantify the associations of temperature, I also considered a class variable that contained the same temperature ranges as those I developed for the photoperiod-temperature comparison presented in above Figure 43. In addition, I added the class variable SEASON, for season of conception. I added three class variables to test geographic variation of sex ratio independently of climate variation and the selected socioeconomic variables: the LATZONE class, including high and low categories based on the latitude demarcations described above; the METROCOUNTY class from the NCHS dataset to designate counties included in a standard metropolitan statistical area (at least one city 50,000 or more); and the DIVISION class, to identify the US Census division reported in the NCHS dataset as the residence of the mother. Finally, each birth was assigned a climate zone (Table 13) based on US Department of Energy 2004 proposed classifications for each US county and compiled by the ICPSR (ICPSR 2008).

Table 13. Proposed US Department of Energy county-based climate zones.

1A	Very hot, moist
2A	Hot, moist
2B	Hot, dry
3A	Warm, moist
3B	Warm, dry
3C	Warm, marine
4A	Mixed, moist
4B	Mixed, dry
4C	Mixed, marine
5A	Cool, moist
5B	Cool, dry
6A	Cold, moist
6B	Cold, dry
7	Very cold
8	Subarctic

The odds ratio results of the non-Hispanic white births model are plotted in Figure 46 and parameter results in Table 14. The fitted model includes 17,583,545 births after missing values were excluded. Model fit statistics are acceptable for both 2 LOG L (χ^2=43, p=0.04) and Hosmer and Lemeshow goodness-of-fit (χ^2=6.233, p=0.62). With better diagnostics and model specification, this model produces essentially the same results as the Allbirth model.

No socioeconomic or geographic division variables fit this model, although Percent Below Poverty Level is nearly significant. Counties with a higher level of poverty produced fewer males; other income variables produced similar results. Preterm births have higher odds for producing males than any other factor considered. Plurality and parity have essentially the same relative contribution to male births as in the Allbirths model. Temperature in the month before conception is a significant influence in the non-Hispanic white births model, but I also evaluated as a categorical variable with the temperature range >=50 and <60 degrees F as the reference variable. Using this range as a reference, children conceived when temperatures in the previous month are greater than or equal to 70 degrees F are more male biased than those conceived during any other temperature range. In this model, conceiving a child in this temperature conditions provides greater odds of a male child than either first or second born children compared to higher birth orders. The other significant temperature range in this model is >=30 and <40, which produced female-biased sex ratios.

Unlike the Allbirths model, number of hours of daylight during the month of conception is significantly associated with sex ratio, the odds of a male birth decreasing with the number of hours of daylight prior to the month of conception (BDAYLEN). In this global model, BDAYLEN functions as a proxy for latitude and season, I believe, but it poorly describes these interactions for a local model. The complexity of this relationship is better described with geographically weighted regression.

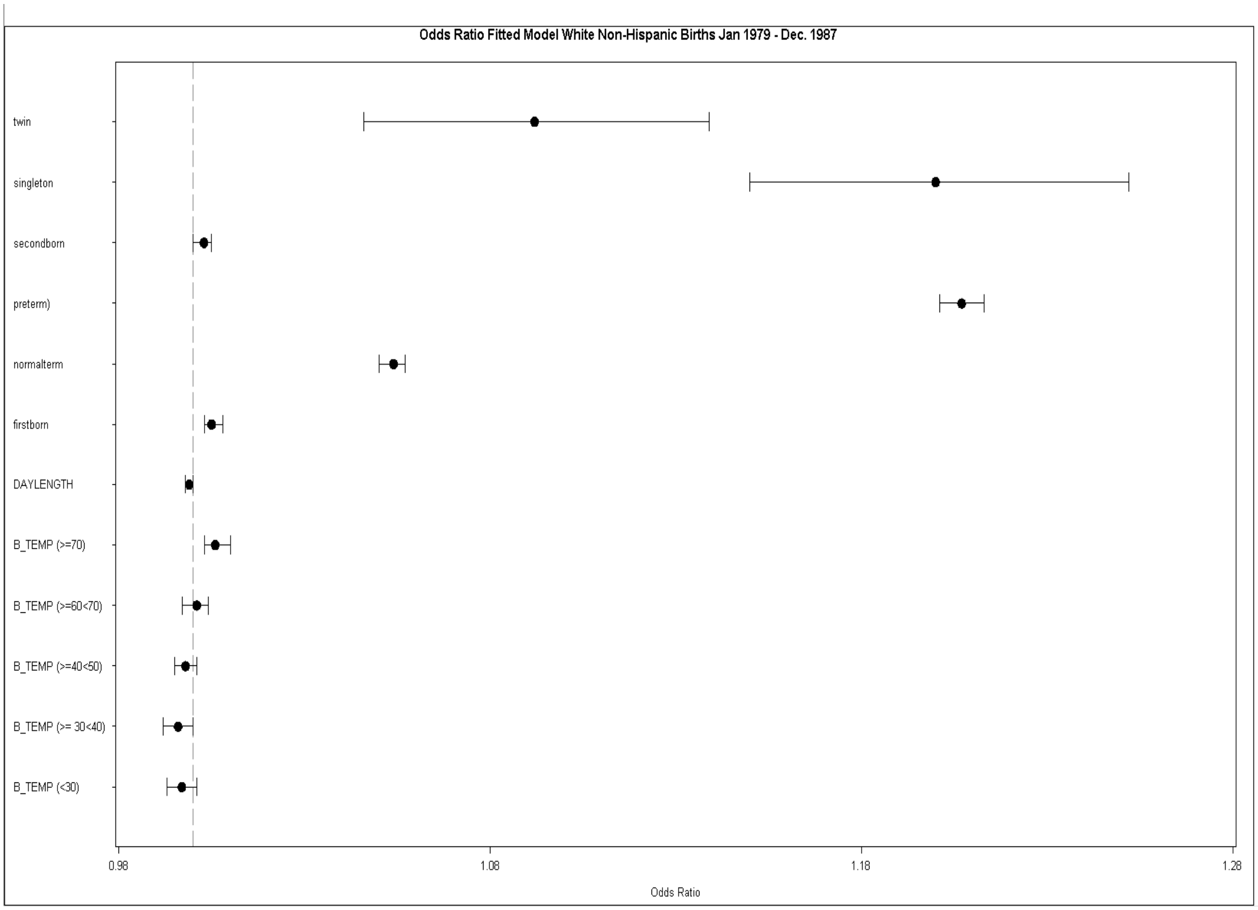


Figure 46. Plot of odds ratio of parameters for fitted logistic regression model of non-Hispanic white births conceived Jan-1979–Dec 1987, odds ratio and confidence range of male birth displayed.

Table 14. Maximum likelihood estimates of parameters for fitted model of all parameters for non-Hispanic white births conceived Jan 1979–Dec 1987, with likelihood of male child as the model estimated.

Parameter	DF	Estimate	Std. Error	Wald Chi-Square	Pr > ChiSq
Intercept	1	-0.1767	0.0223	62.718	<.0001
BTMP >=30 and <40	1	-0.00389	0.00192	4.1136	0.0425
BTMP >=40 and <50	1	-0.00198	0.00173	1.3113	0.2522
BTMP >=60 and <70	1	0.000665	0.00162	0.168	0.6819
BTMP <30	1	-0.00278	0.00211	1.731	0.1883
BTMP >= 70	1	0.00619	0.0017	13.2568	0.0003
Parity (firstborn	1	0.00511	0.00124	16.964	<.0001
Parity (secondborn)	1	0.00286	0.00129	4.8846	0.0271
Gestation (Normal)	1	0.0522	0.00183	813.7824	<.0001
Gestation (PreTerm)	1	0.1884	0.00249	5741.548	<.0001
BDAYLEN (Hours)	1	-0.00091	0.000412	4.9038	0.0268
Plurality (Singleton)	1	0.182	0.0216	70.7448	<.0001
Plurality (Twins)	1	0.0877	0.0219	16.0823	<.0001

Spatial Relationship of Seasonal Temperature and Sex Ratio at Conception

As I have shown, the temperature in the month before conception is significantly positively correlated with an increase in the likelihood of the conception of males in US births. To explore the association of temperature and US geography during the study period, I constructed a local model of seasonal temperatures and sex ratio lagged to conception season. For each of the four seasons, I aggregated all non-Hispanic white births conceived between January 1979 and December 1987. The temperature in the month before conception was averaged for each division (B_TMP).

Using the ArcGIS OLS linear regression model, I tested several global models using the seasonally aggregated lagged sex ratio by division and a number of climate variables averaged by division, including multiple variable models (Table 15). No significant association between sex ratio and climate variables was found for sex ratio lagged to winter and spring conceptions, but sex ratio lagged to summer and fall was significantly associated with B_TMP, which agrees with the robust linear regression model result for sex ratio at conception by latitude zones reported in Table 8. However, these models also have diagnostic issues. The summer model fails the Koenker (BP) statistic (9.057, $p=0.002$) for biased standard errors, directing the use of the robust probability estimate, which is only nearly significant ($p=0.0058$). The fall season model also fails the Jarque-Bera statistic (1063.98, $p<0.0001$), indicating a non-normal distribution. Although the OLS model fails for winter and spring, and has diagnostic issues for summer and fall, its results are sufficiently encouraging to explore a local geographically weighted regression model.

Using the same seasonal temperature and sex ratio parameters, I constructed a local spatially adaptive model using the ArcGIS 9.3.1 geographically weighted regression (GWR) tool. The spatial weighting kernel selected for the GWR model was adaptive, which, according to Fotheringham et al. (2002), covers most applications and may be preferred because the observations of climate divisions in the west are less dense than those in the east. The adaptive bandwidth method did not produce notably different results from the crossvalidation (CV) bandwidth selection method. The AICc (corrected Akaike Information Criterion) was used to calculate the complexity of model and to compare its fit against the global OLS model; this method is also preferred by Fotheringham et al. (2002). AIC and R^2 values of the OLS and the GWR models are compared in Table 16.

The R^2 of the GWR models is improved over the OLS R^2 in each season. However, as recommended by Fotheringham et al. (2002), AICc of both models can be compared to determine whether the local GWR model improves the fit of the global OLS model. A difference of at least 4 between the models is suggested as a criterion for sufficient difference. Based on this criterion, only the non-significant winter model is improved by GWR over OLS.

The deficiencies of both these models are shared by the general deficiencies of OLS in assessing sex ratio differences, which I have already discussed. However, mapping the coefficient surface of each seasonal GWR model does provide insight into the spatial and temporal nonstationarity of sex ratio variation in US births during this period.

Coefficient ranges vary with each seasonal model and are not meaningful when compared across seasons, so I have presented each seasonal GWR coefficient surface as a separate figure

(Winter: Figure 47; Spring: Figure 48; Summer: Figure 49; Fall: Figure 50). Accompanying each coefficient map is a choropleth map of mean temperatures in the month before conception for each season. Therefore, a B_TMP seasonal map of climate division temperatures for Summer shows, for example, the mean of monthly temperatures for May, June, and July.

Table 15. OLS regression of seasonal temperature and sex ratio at conception, non-Hispanic white births conceived 1979–1987, by season for 339 climate divisions. R^2 for each seasonal model and Moran's I for spatial autocorrelation of seasonal sex ratio at conception also reported.

Variable	**Coefficient**	**StdError**	**t-Statistic**	**Probability**	**Robust_SE**	**Robust_t**	**Robust_Pr**
Winter (n=339; R^2 = 0.00006; Moran's I = -0.019,p=0.470							
Intercept	0.513499	0.001519	338.055	0.000000*	0.001649	311.316918	0.000000*
BTMP	0.000006	0.000041	0.146651	0.883485	0.000043	0.139909	0.888805
Spring (n=339; R^2 = 0.004;Moran's I = 0.007, p=0.666							
Intercept	0.516009	0.00219	235.6395	0.000000*	0.002101	245.559155	0.000000*
BTMP	-0.000056	0.00005	-1.12241	0.262481	0.000043	-1.292504	0.197075
Summer (n=339;R^2=0.015;Moran's I = -0.034, p = 0.17)							
Intercept	0.50109	0.00529	94.71808	0.000000*	0.006734	74.416243	0.000000*
BTMP	0.000176	0.000077	2.283975	0.022981*	0.000096	1.837454	0.067025
Fall (n=339; R^2= 0.02; Moran's I=0.021, p=0.028)							
Intercept	0.503488	0.004149	121.3488	0.000000*	0.004638	108.567173	0.000000*
BTMP	0.00017	0.000064	2.633089	0.008845*	0.000071	2.407696	0.016578*

Table 16. Comparison of Seasonal OLS and GWR models for seasonal sex ratio at conception, non-Hispanic white births, conceived 1979–1987.

Season	**OLS R^2**	**OLS AICc**	**OLS Model p.**	**GWR R^2**	**GWR AICc**
Winter	0.000064	-2284.100590	0.88	0.0014	-2280.03
Spring	0.0037	-2240.8	0.26	0.0086	-2238.07
Summer	0.015	-2200.5	0.02/0.055	0.022	-2198.5
Fall	0.020	-2273	0.008	0.048	-2273.4

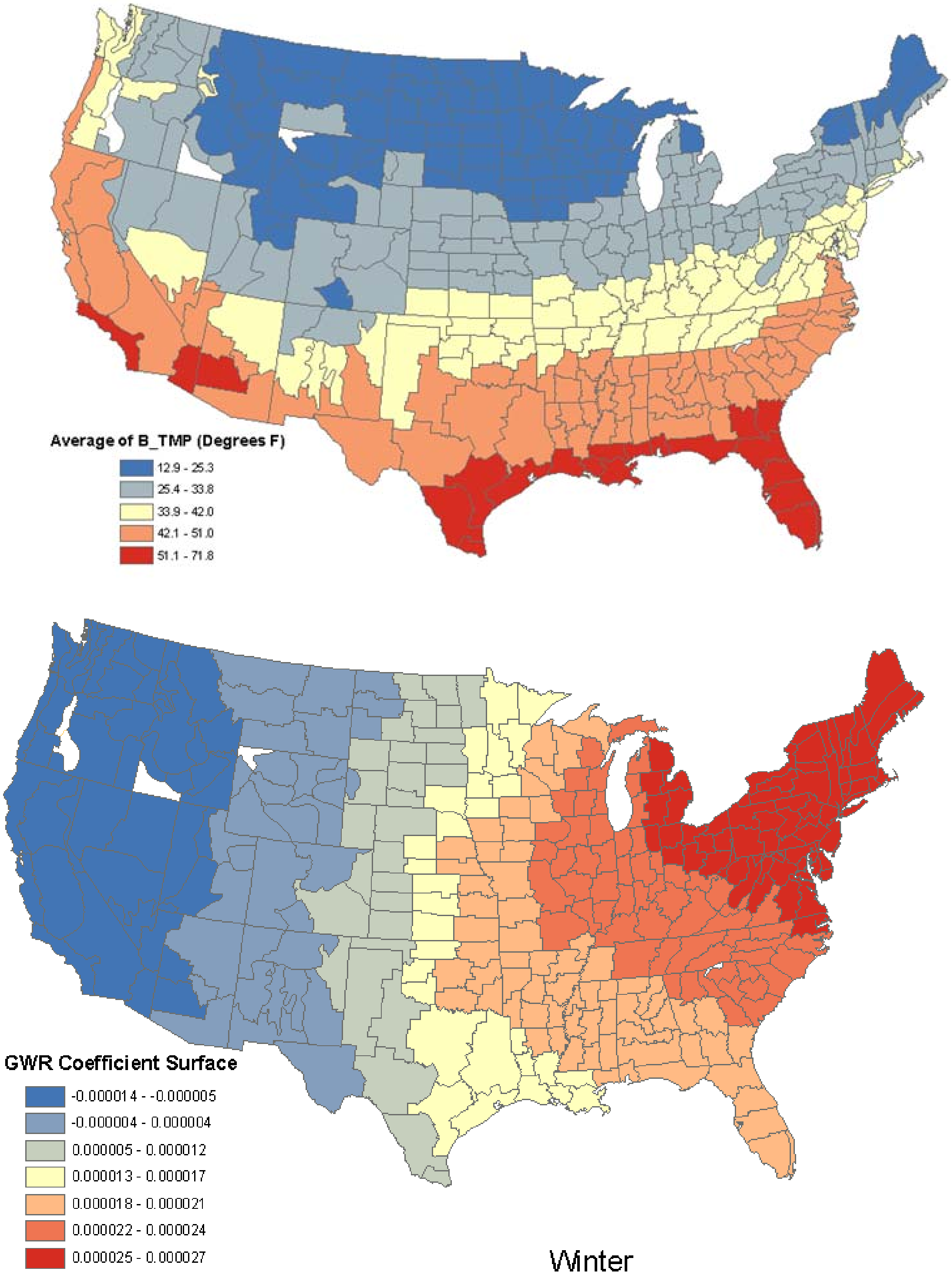


Figure 47. GWR coefficients for sex ratio of winter conceived births and mean temperature before conception, non-Hispanic white births, 1979–1987.

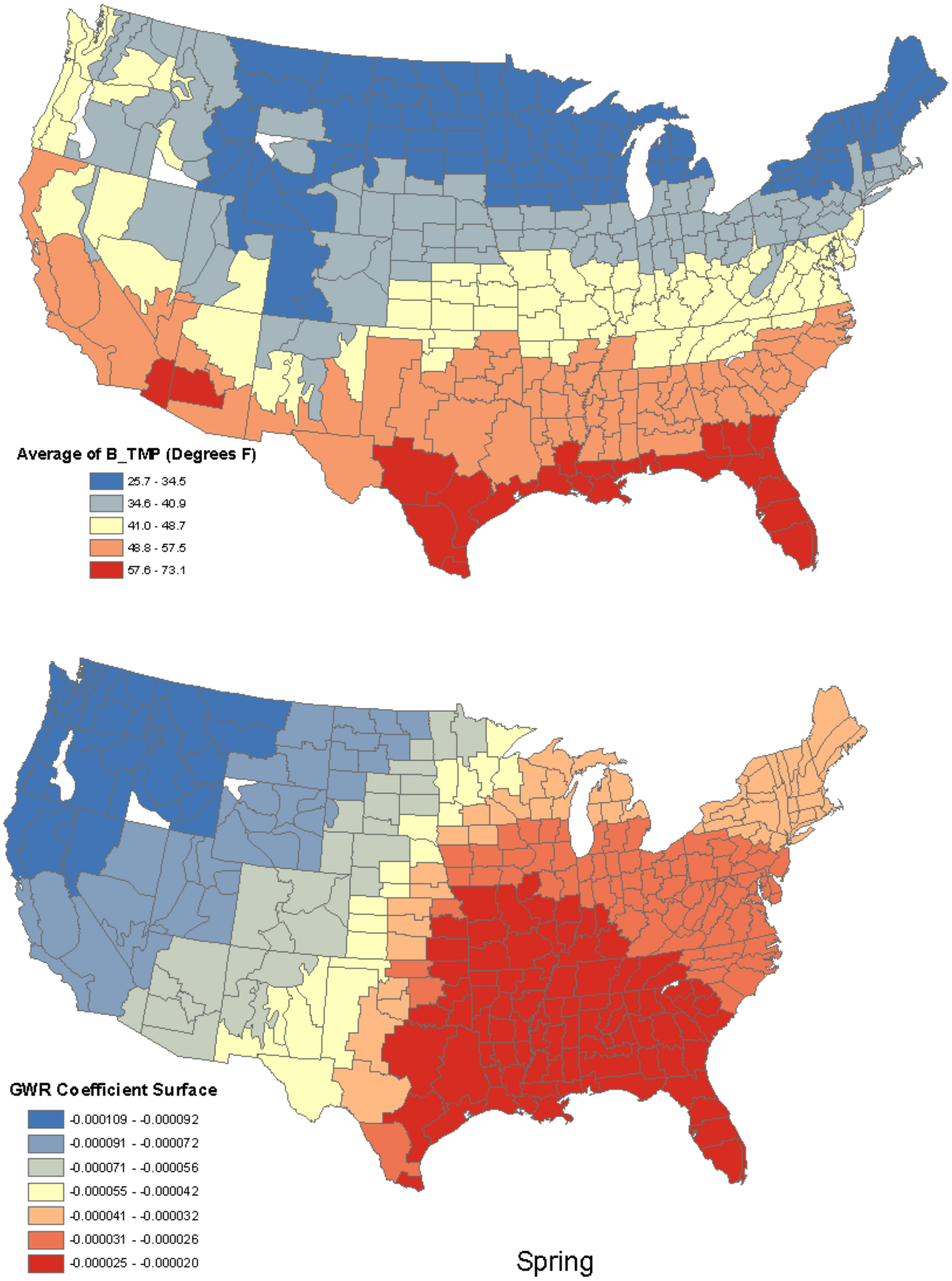


Figure 48. GWR coefficients for sex ratio of spring conceived births and mean temperature before conception, non-Hispanic white births, 1979–1987.

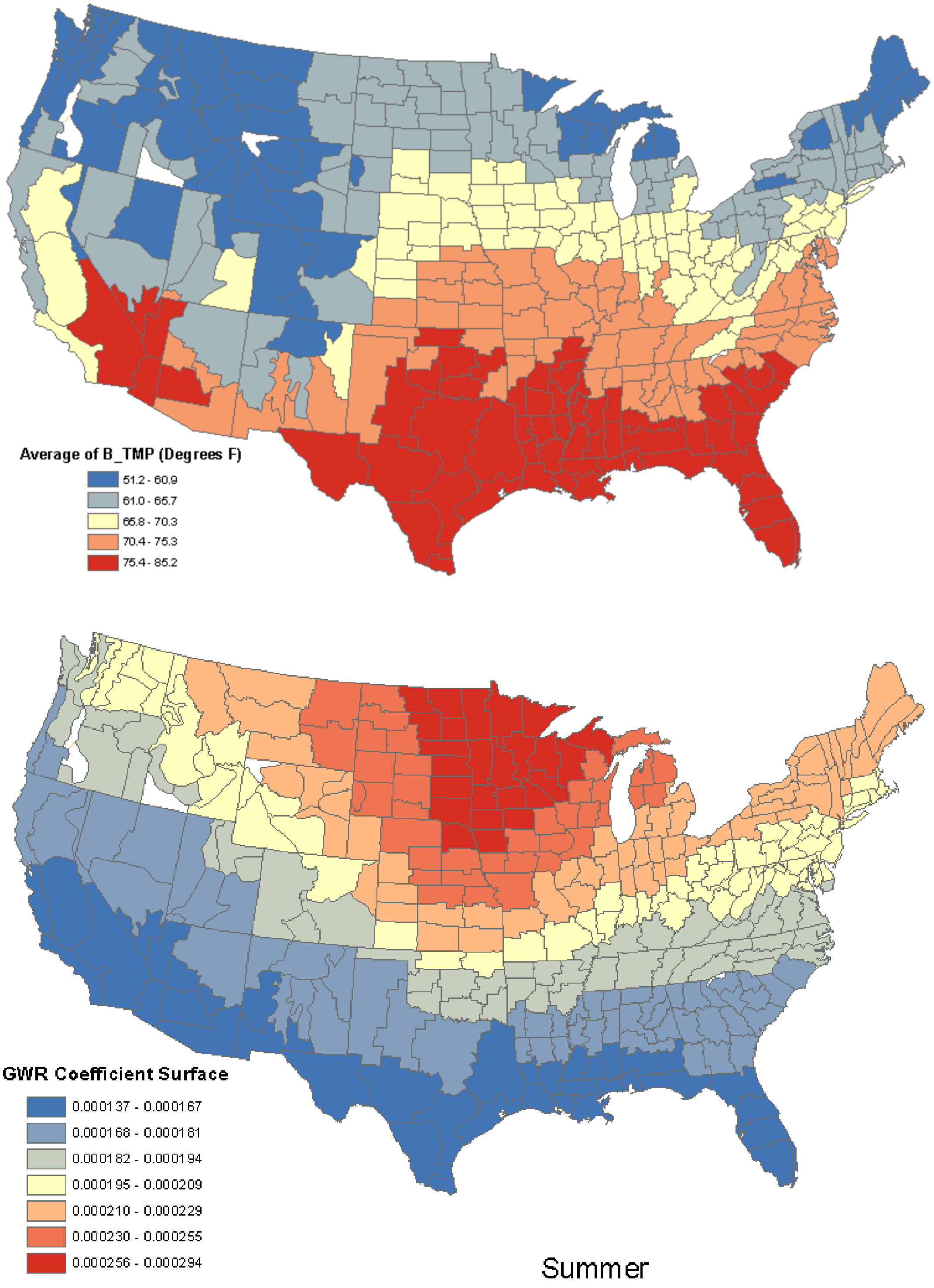


Figure 49. GWR coefficients for sex ratio of summer conceived births and mean temperature before conception, non-Hispanic white births, 1979–1987.

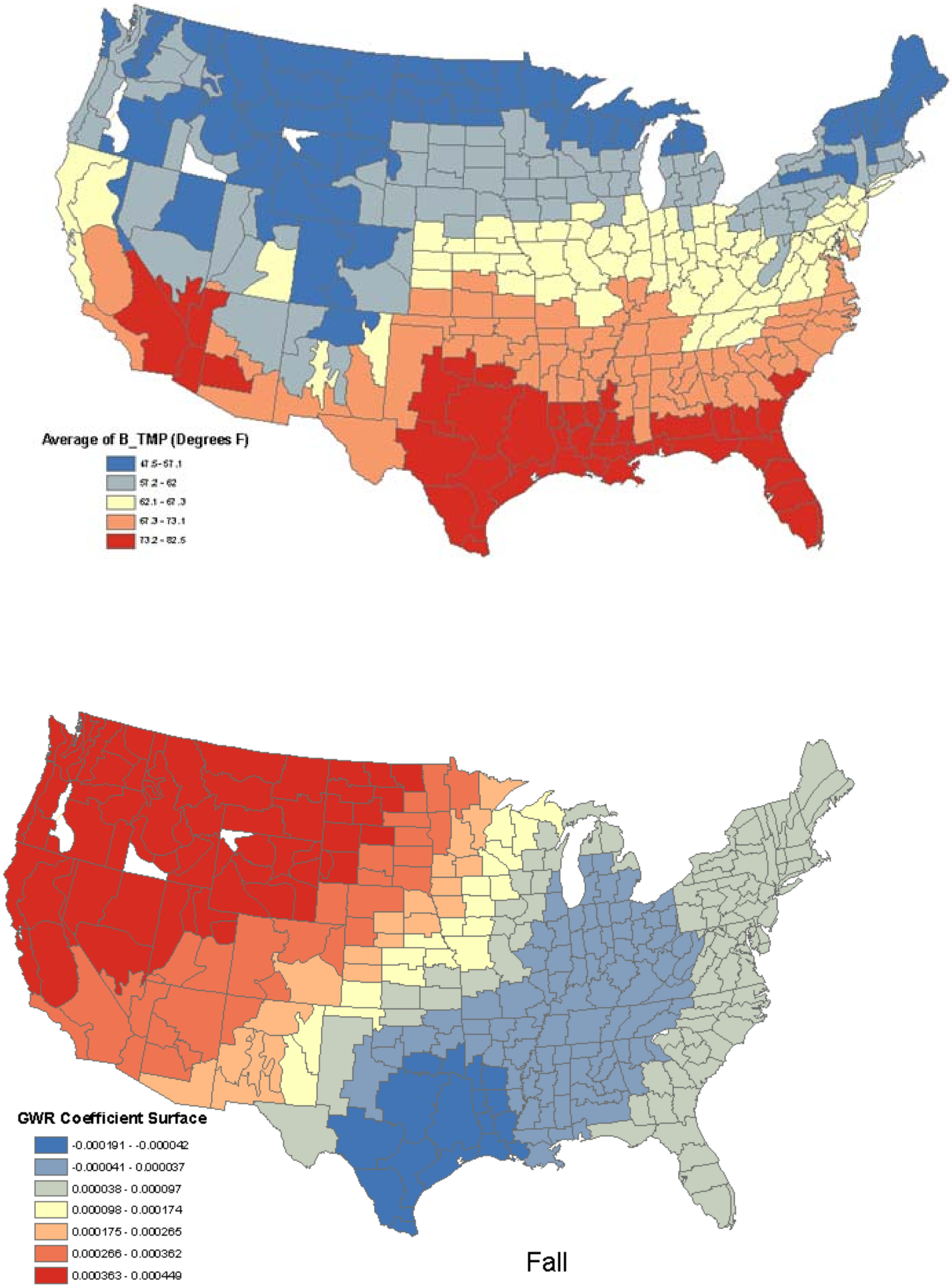


Figure 50. GWR coefficients for sex ratio of fall conceived births and mean temperature before conception, non-Hispanic white births, 1979–1987.

The patterns in these maps show that the association of male conception likelihood and temperature in the month before conception has distinct geographic variation by season. Births conceived in summer, the season of highest male conception, have a lower coefficient of male births related to temperature in lower latitudes (Figure 49) and have the most latitudinal segmentation of all four seasons. In this model, the high temperatures of low latitudes in the summer are not associated with relatively higher sex ratios compared to summer temperatures in the upper Midwest, perhaps related to the same suppressive effect of high summer temperatures that can in low latitudes on smoothed maps of seasonal birth rates.

The distribution of temperature/sex ratio coefficients for spring strongly resembles the smoothed maps of birth rates for this period (Figure 31). Sex ratios are highest in the Southeast, and lowest in the Northwest, the strongest positive correlation of temperature and sex ratio across all climate divisions. The fall pattern somewhat mirrors the spring pattern, although the lowest coefficient values are centered in Texas, which also has its lowest birth rates of the year in this season. The highest coefficients for temperature associations with sex ratio in the fall are in the West, with a center in the Northwest and upper Rocky Mountain states. The coefficient surface for winter conceptions has the least relationship to the latitudinal variation of temperate. The lowest coefficients are in the West, while the highest are in the Northeast, including the cold winter states of New England. This surface is more suggestive of the longitudinal variation of winter precipitation (Figure 35) than the latitudinal and elevational variation of temperature most strongly suggested by the summer coefficient surfaces. Seasonal precipitation did not, however, fit any global model I constructed for geographic analysis.

Because each figure displays only the geographic variation of coefficient surfaces for an individual season, they cannot be compared to one another. In addition to seasonal variation there is a geographic nonstationarity to sex ratio that appears to be related to climatic regime. The smoothed sex ratios for all non-Hispanic births during this period are shown in Figure 51, along with the composite annual temperatures for the same period created with the NCDC US Climate Division center mapping page (NOAA 2011).

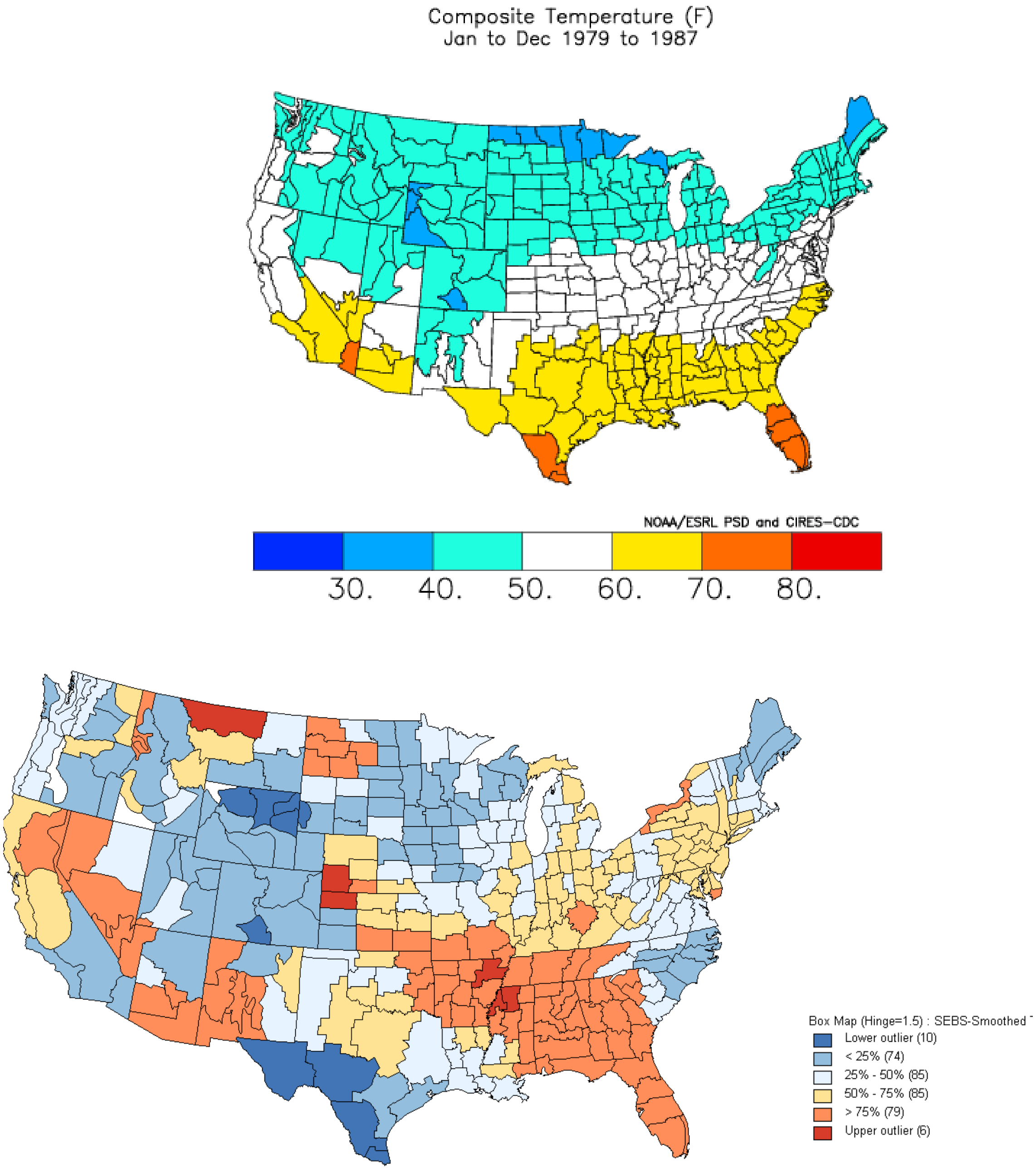


Figure 51. Smoothed sex ratio at conception, non-Hispanic white births conceived 1979 to 1987. (Spatial empirical Bays smoothing method, box map-hinge = 1.5, threshold distance weighting). Top map displays composite mean temperature by climate division for the same period (NOAA 2011).

While temperature and the likelihood of a male birth are positively correlated during this period, the relationship is not linear and varies by US region. The nonstationarity of sex ratio at conception in US births appears to be strongly associated with the relative annual mean temperature of the climate division. Sex ratio is highest at low latitudes, particularly the Southeast. The coefficient surfaces of all seasons for this period indicate that the relationship suggested by the positive correlation of temperature and sex ratio is complex. Spring warmth is possibly favorable for male conceptions in the warm Southeast, but relatively fewer males are conceived in summer there compared to the summer rate for other regions. Again, this geographic disparity in sex ratio at birth may be related to the suppression of fertility that occurs in warm climates during summer months (see, for example, Lam and Miron 1996). Outliers like the low sex ratio in southern Texas may be related to unspecified socioeconomic factors, such as underreporting of Hispanic births.

Time series analysis of this study period also shows that sex ratio varies seasonally as well as geographically, with some conformance to the annual fertility rhythm. However, the peak of sex ratio conception occurs prior to the birth rate peak and annual patterns frequently have a double humped pattern. The relationship of SRB to fertility and its spatial and temporal variation in US climate divisions is a necessary baseline to understand better the decline in sex ratio at birth that has occurred during the last portion of the 20th century. I examine this decline and its relationship to temperature in the next chapter of this study.

Chapter 5. US Sex Ratio Decline and Climate Associations

Using findings about seasonality and geographic structure of the US sex ratio and birth rate from 1979–1988, I examine in this chapter a longer period of birth data during which a significant decline in the SRB can be detected. I test the temperature and SRB associations I found in the geographic study of the previous chapter in the context of the increase in US temperatures recorded during the 1979–2002 period. This analysis is limited to the 403 largest population counties for which NCHS provides continuous geographic information over this period in public records. The sections of this analysis are:

Demographic components of the US decline in sex ratio at birth. Race, ethnic origin, maternal age, partnership status, and maternal education have been shown to vary with the sex ratio at birth. Significant changes in the composition of these components have occurred during the study period. I describe these and assess whether these changes could partially explain the decline observed during the study period.

Economic stress during the study period. Based on the work of Catalano (2003), I briefly look at the relation of the consumer confidence index to the sex ratio at conception for the study period. This US level variable measure of socioeconomic condition is also examined in the global model that considers individual and county level variables.

US birth rate seasonality and sex ratio among population groups. Although the primary subject population of this study is non-Hispanic whites, I also briefly analyze trends in birth rate, sex ratio and seasonality among the overall US population, Hispanic whites, and non-Hispanic blacks, compared to non-Hispanic whites to determine if trends are also present in these populations.

Global model of US sex ratio at birth and climate change association. In the final analysis, I plot seasonal and temporal declines of SRB by latitude zone and compare them to the concurrent changes in temperature over this period. I construct a model of US climate change that considers individual biological and social factors, socioeconomic conditions, geographic variation, climate variables, and significant changes in baseline climate variables.

Demographic Components of US Decline in Sex Ratio at Birth

I found no significant declines of sex ratio at birth in the 1979–1988 dataset, but a number of authors have established that SRB has declined in the US beginning as early as 1970 (Mathews and Hamilton 2005). To examine the spatial and temporal character of the US sex ratio and its relation to climate, I extracted from public use micro-file data birth data using the same methods as for the geographic study period, but only for those largest 403 counties for which NCHS records county of residence throughout this period (see Appendix 2 for a listing of these counties). Also to maintain confidentiality of birth data, NCHS does not include the day of birth for the later phases of the study period, so the method I employed to calculate month of conception uses the month reported as the last menstrual period (LMP) rather than subtracting gestation weeks from the date of birth. Although constrained geographically and with a potentially higher error for detecting month of conception, this longer time scale allows examination of climate variables over a period in which significant decline in the US sex ratio can be detected. Over 67 percent (approximately 62.8 million births) can be attributed with monthly climate values from the 339 climate divisions during this period.

I again concentrate my analysis on non-Hispanic white births in those 403 largest counties for which a LMP month of conception can be calculated. This is approximately 39.4 percent of the total 93,076,335 births (counting 1,865,794 records classed as 50 percent recordweight) in NCHS records for the period 1979 to 2002. To remove trailing effects, I do not analyze births whose conception occurred after December 2001.

As far as I know, climate change has not been implicated by scholars in the decline in the US sex ratio at birth. Although seasonality has been detected in US sex ratio (Slatis 1953, Lyster 1971), this variation has not been associated with temperature in the US. I have shown that temperature in the month before conception is significantly associated with a higher sex ratio for US births, but this relationship is complicated by geographic factors that can partially be explained by latitude and associated seasonal differences

Before exploring climate relationships over this longer study period, however, changes in biological, cultural, and demographic factors during the period should also be considered for their hypothesized effect on US SRB. Some of these cannot be examined in the NCHS data or other data I have collected, such as the increased use of fertility drugs for conception, particularly among older women, changes in the western diet, or an increase in maternal eating disorders. Other hypotheses do warrant review of NCHS data, particularly those related to changes in maternal age, gestational period, and changes in the race and Hispanic origin of the US population of women in childbearing years.

The most comprehensive previous study of these potential effects on SRB was by Branum et al. (2009), who examined the decline in the US SRB related to changes in plurality, gestational age and race/ethnicity using 1981–2006 NCHS data. They found that the decline in the overall US SRB is largely limited to the group comprising the largest number of births: white singleton births born at term. They also found that male proportion in multiple births increased over this period, despite evidence that fewer males are born in sets of twins than in singletons (James 1975; Jacobsen et al. 1999b) and that drug induced fertility measures may lead to increased female births (Sampson et al. 1983). Nonetheless, sex ratio differed significantly according to plurality among white births, but not black births. Adjustments for gestational age tempered the trends among white births, but had no effect on black birth male proportion. Adjustment for Hispanic ethnicity had no impact on the black male proportion. Hispanic ethnicity was a significant factor in white male proportion, but it was negated by changes in gestational age trends. The sex ratio differences among subpopulations examined were perhaps partially explainable by differing gestational age structure, but the differences in how various potential influences affected these subpopulations led them to believe that a single mechanism is unlikely to explain the overall decrease in the US sex ratio.

I also examined these factors for the 1979–2001 study period, which concludes slightly earlier (2002 v. 2006) than that studied by Branum et al. (2009), so I did not see the leveling of SRB decline reported by these authors. I have the same general conclusion as these authors, which is that the decrease in the US sex ratio cannot be explained by changes in plurality, gestational age structure of births or changes in the racial or ethnic profile of mothers. In fact, I found that the decline in non-Hispanic white SRB is even steeper when these factors are controlled.

Because of the increase in the total proportion of Hispanic births during the study period and the lower SRB of this population, control for this factor is essential in isolating effects possibly associated with climate. For a number of time series perspectives presented here, I control for non-Hispanic births throughout the 1979–2001 study period, although Branum et al. (2009) only examine this effect after 1989 when standard birth certificate reporting was established for Hispanic origin. My data, which begins for births recorded as early as 1979 (and conceived in 1978), underreports Hispanic origins in certain states during the early part of the study period. However, as I noted in the methods chapter, an estimated 90 percent of Hispanic births occurred in states reporting this data in 1980 and increased thereafter. Further, since lower SRBs are consistently reported for Hispanics, the effect of underreporting of these births in the earlier part of the study period would be to decrease the non-Hispanic SRB. Therefore, the slope of the true decline in non-Hispanic white births would be even greater than reported by such researchers as Branum et al. (2009).

Changes in gestational age structure warrant close attention for their potential influence on recent SRB patterns. More males are born prematurely than females and the rate at which they survive can affect SRB statistics for live births. One of the most notable changes in the reproductive ecology of US births during the study period is the rate at which males and females survive to a live birth. Although the rate of preterm births has declined in most developed countries, it has increased in the US in the last three decades. The number of preterm births in the US has increased about one-third from the early 1980s to 2006 (Martin et al. 2008). This is at least partially attributable to the increase in the induction of labor and Caesarian delivery in preterm births. These same practices have resulted in the reduction of the number of postterm births from earlier periods.

These trends are apparent in the study data (Figure 52), which shows that the percent of deliveries to non-Hispanic whites within normal gestation period increased from 75.8 percent in 1979 to 82.9 percent in 2001. At the same time, the number of postterm births considerably declined, from 17.0 percent in 1979 to 6.6 percent in 2001. Preterm births during this period increased from 7.1 percent to 10.4. These values agree in general magnitude with those in several studies that have found significant changes in preterm births in all populations in the US. Ananth et al. (2005), for example, found that preterm rates increased by 14 percent in whites and decreased by 15 percent in blacks from 1989 to 2000. The rate of medically induced preterm birth increased by 55 percent among whites and 32 percent among blacks.

Because preterm births are male biased and postterm births are female biased relative to those of term gestation, we would expect that, other factors being equal, the increases in the rates of preterm births and the decrease in that of postterm births during the study period would result in a net increase in SRB. However, not only has overall SRB declined, but it has declined for preterm and postterm births to a greater degree than for normal gestation births (Figure 53).

Not considered by Branum et al. (2009) but potentially also important as a factor in SRB are changes in the age structure of mothers. Using the four maternal age categories I developed for logistic regression class models, a large shift from births to mothers 20–30 to mothers age 30–39 can be seen (Figure 54).

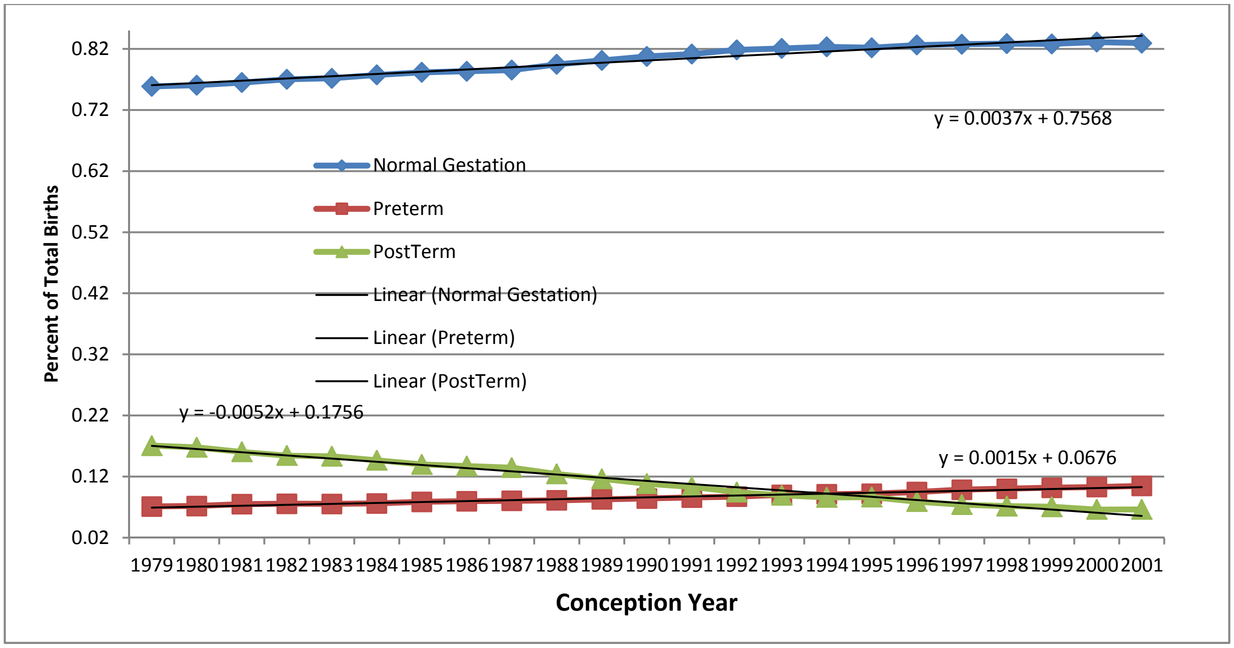


Figure 52. Annual percentage of normal, preterm, and postterm non-Hispanic white births, US large counties, 1979–2001.

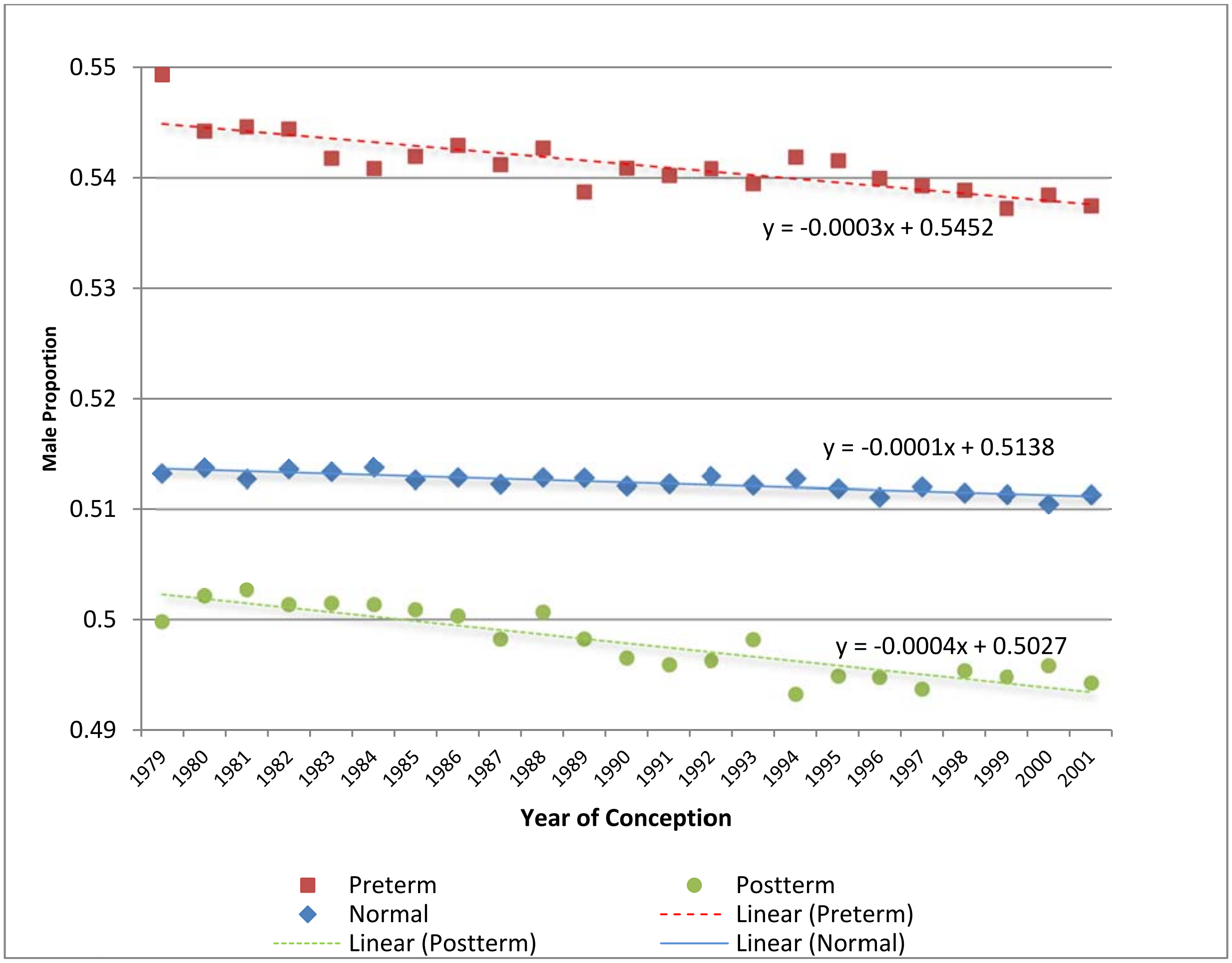


Figure 53. Sex ratio lagged to conception for preterm, normal, and postterm non-Hispanic white births, US large counties, 1979–2001.

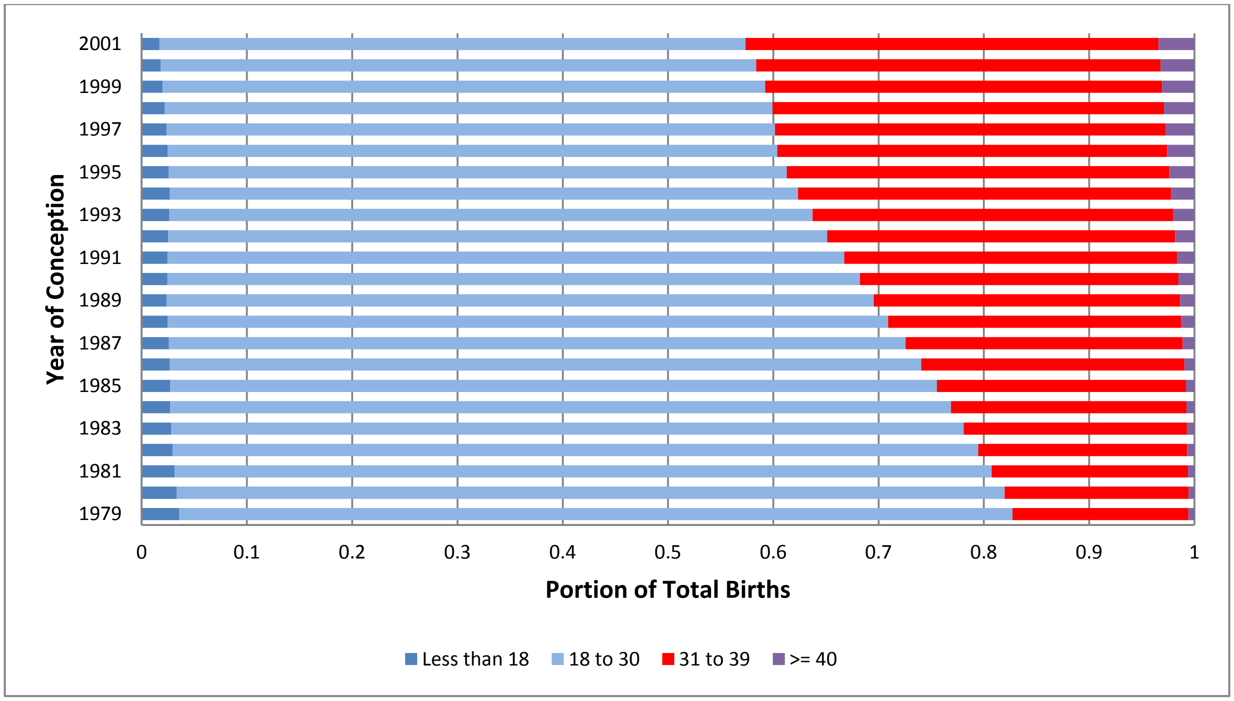


Figure 54. Portion of non-Hispanic white births by age category of mother, births conceived 1979 – 2001.

NCHS (2005) estimated that the average age of all women giving birth rose from 21.4 years in 1970 to 25 in 2006. In the 1979–2001 dataset, the number of mothers aged 18–30 declined from 79.1 percent to 55.7 percent, while those in the 31–39 category increased from 16.7 percent to 39.2 percent. Births to mothers under 18 years declined from 3.5 to 1.6 percent, while births to mothers 40 and over increased from 0.5 percent to 3.5 percent. Some researchers have found that older women are generally more likely to give birth to females than younger women (e.g., the Almond and Edlund 2007 study of US natality data from 1983 to 2001). Others find that parity confounds this influence; younger women who have had at least one child are more likely to produce boys than older women (Braza 2004). Given that some literature supports a maternal age effect, the increase in mean age of motherhood in US mothers could partly explain the decline in sex ratio at birth during the study period.

I found that the estimated sex ratio at conception of mothers in the 31–39 age category had not declined significantly (y=-.00001x, p=0.629, R^2 = 0.01) during the study period when regressed against year of conception; however, it is generally lower than the sex ratio at conception of mothers in the two younger categories. Therefore a shift of the proportion of total births towards the highest age category could be responsible for part of the decline in SRB (Figure 55).

However, the SRB of children born to mothers aged 18–30, the greatest portion of mothers giving birth during this period, declined significantly over this period ($y=-00005x$, $p=0.004$, $R^2=0.334$). SRB in under-aged mothers and those aged 40 and over also declined, but not significantly ($y =-0.00008x$, $p=0.30$, $R^2 = 0.05$; $y=-0.0001x$; $p=0.058$, $R^2=0.001$, respectively).

While it is possible that the increase in the mean age of mothers may be a factor in the decline of SRB, it appears that the decline in sex ratio at birth among non-Hispanic white mothers is not attributable to either maternal age or gestation period changes during this period. The sex ratio of children born to non-Hispanic white mothers aged 18–30 with normal gestation periods has declined more than the overall rate of non-Hispanic white mother sex ratio at birth. Also, the sex ratio at birth of firstborn, singleton children born to mothers 18–30 with normal gestation has also declined, so changes in family size or multiple births due to, for example, increased use of fertility drugs among woman who had delayed having children, cannot be identified as significant. Because of the decline of SRB in all maternal age categories of non-Hispanic white births, I conclude that changes in the maternal age structure of mothers are only partially responsible for the decline in sex ratio among non-Hispanic white mothers.

In general, the net effect of changes in obstetric factors and fertility demographics during this period is to obscure an even steeper decline in sex ratio due to other variables not considered in the above analysis. This decline can been seen in trends for non-Hispanic white births with material age, gestation, parity and plurality considered (Figure 56). As this figure shows, the slope of decline for non-Hispanic white births conceived from 1979–2001 steepens for births to younger mothers with normal term births, and also when these are limited to first born singleton births. Clearly other factors are acting to reduce sex ratio among this demographic segment.

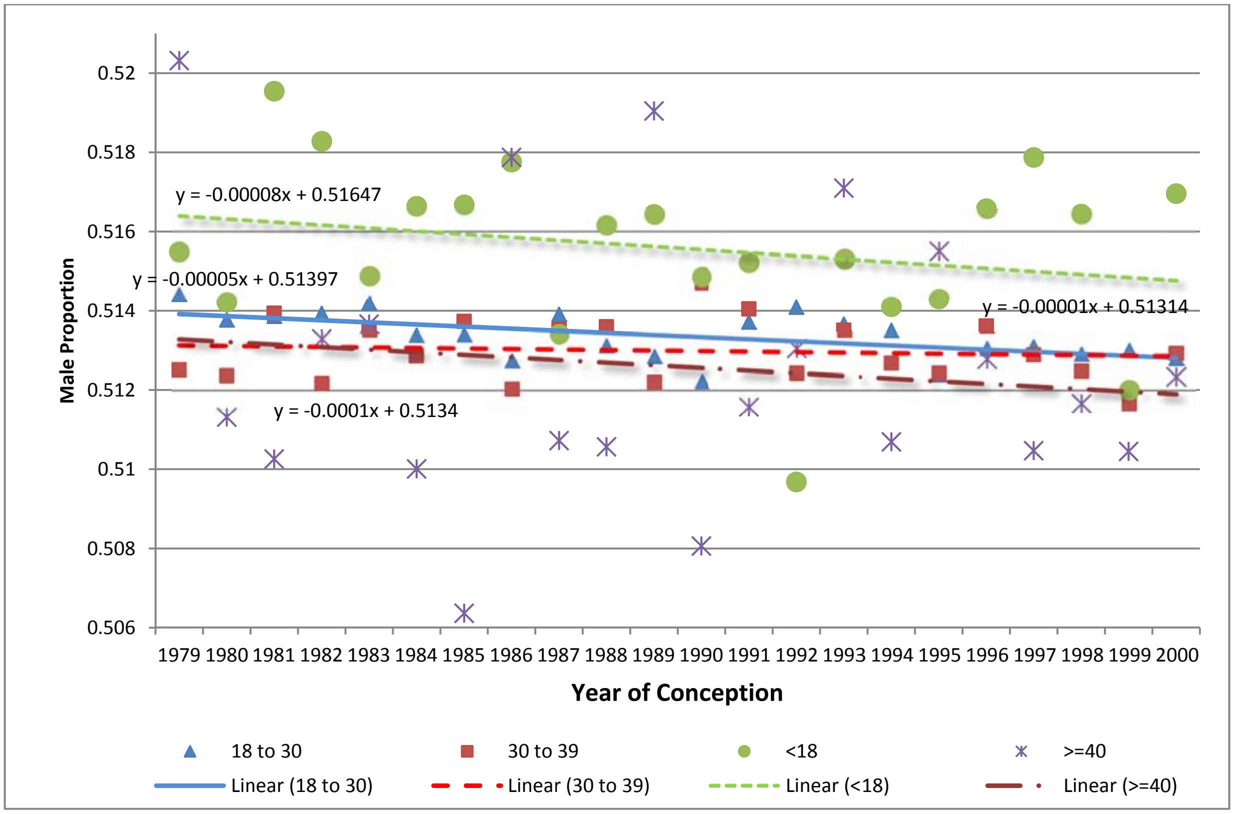


Figure 55. Sex ratio lagged to conception month by age category of mother, non-Hispanic white births US large counties, 1979–2001.

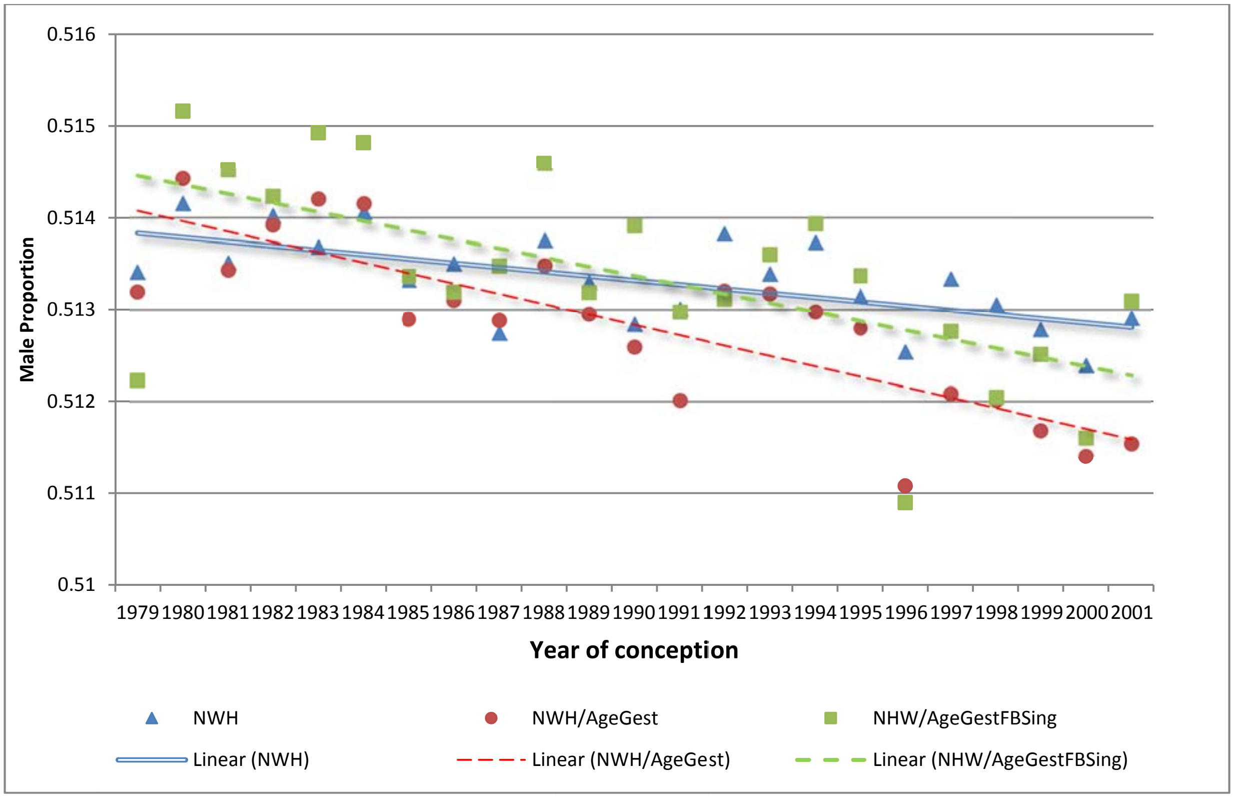


Figure 56. Sex ratio lagged to conception year for all non-Hispanic white births (NHW), non-Hispanic white births to mothers aged 18 to 30 with normal gestation (NWH/AgeGest) and NWH/AgeGest births for firstborn singletons only.

Economic Stress During the Study Period

Exogenous factors that should be considered in an evaluation of influences on SRB include national economic conditions. Catalano et al. (2005) found significant support for a sex ratio economic stress hypothesis in separate studies in Germany and California. However, the 1979–2001 period was a particularly prosperous one for US citizens, beginning with recovery from high interest rates in the late 1970s and ending with the burst of the dot-com bubble in March 2001 and the terrorist events of September 2001. A suitable measure of the perception of economic wellbeing during this period is the Consumer Confidence Index (CCI), a monthly index published by The Conference Board, an independent research organization that developed the index as quantitative measure of the relative consumer optimism about the economy (The Conference Board, 2011). No significant association was found between the

CCI and conception sex ratio values among non-Hispanic white children from January 1979 to December 2001 (Figure 57). In fact, the CCI is at its highest during this period when sex ratio values are lowest. Either the decline in SRB is not associated with the economy during this period, or there is a negative association between high consumer confidence in the economy and the birth of males. Economic stress does not appear to be a significant factor in the US sex ratio decline during this period.

US Birth Rate Seasonality and Sex Ratio among Population Groups.

Given that national level economic conditions and demographic and obstetric changes cannot account for the decline in the overall US sex ratio nor that among non-Hispanic whites, it is reasonable to assess changes in the US sex ratio against associated changes in climate variables during this period, particularly temperature. I again use seasonal birth rates to begin this analysis, but I expand my initial analysis to show seasonal birth rates for all births, non-Hispanic white births, non-Hispanic black births, and Hispanic white births. Time series analyses of birth rates using the SAS time series forecasting tool using the methods described in the previous chapter shows that the seasonality of US birth continues to be strong among all these groups during the study period (Figure 58).

A log seasonal exponential smoothing equation using RMSE provides the best fit for the monthly pattern of birth variation during this period, except for non-Hispanic black births, for which a seasonal exponential smoothing method provided a better fit. For each group, R^2 values for the predictive seasonal model exceeds 0.90.

Two nuances in these patterns are notable. First, there is a slight reduction in the amplitude of the overall birth rate during the latter part of the study period. This may be partly attributable to the reduction in amplitude during the same period for non-Hispanic black births, but this reduction can also be seen in births to non-Hispanic white and Hispanic white mothers. Second, while each subgroup displays remarkable similarity in their seasonal patterns over the study period, the patterns of seasonality among non-Hispanic black births and Hispanic births are more similar to each other than they are to the seasonal pattern of non-Hispanic white births.

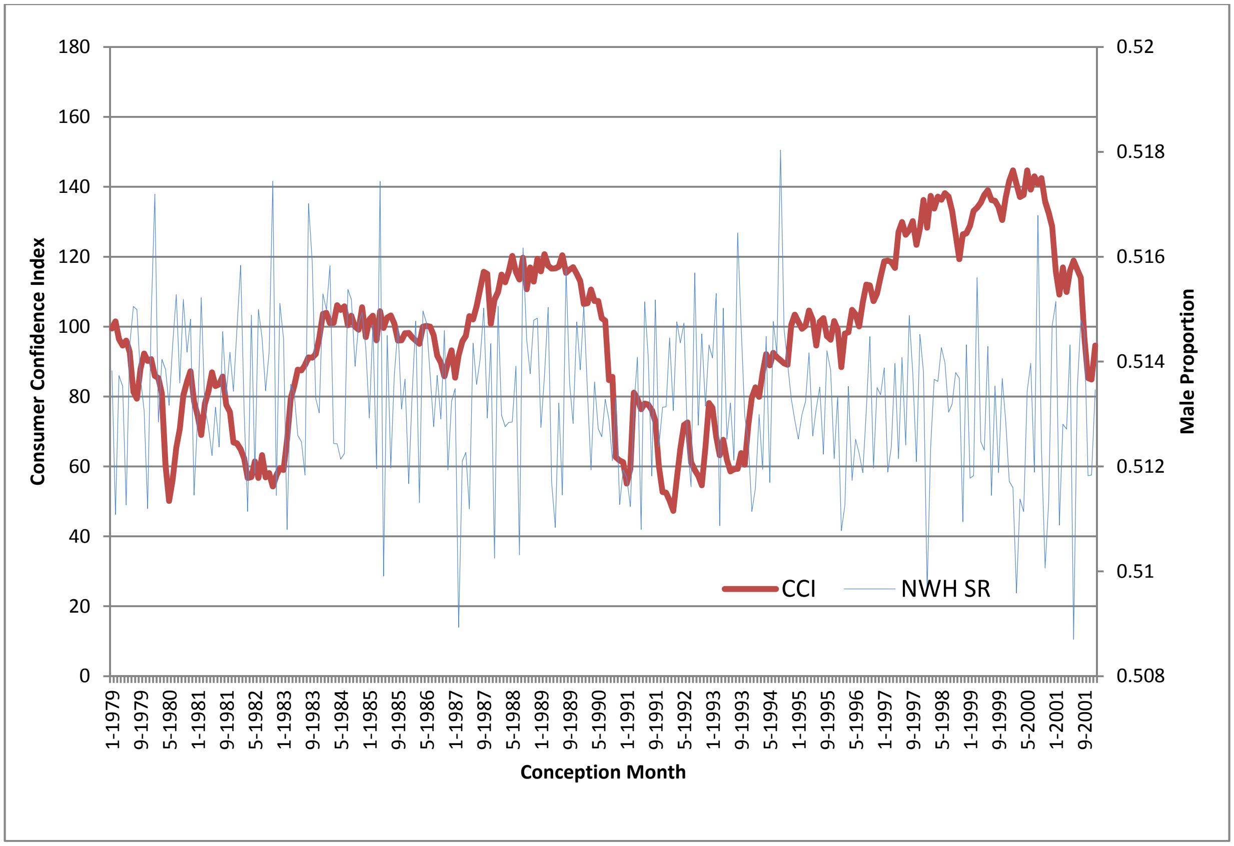
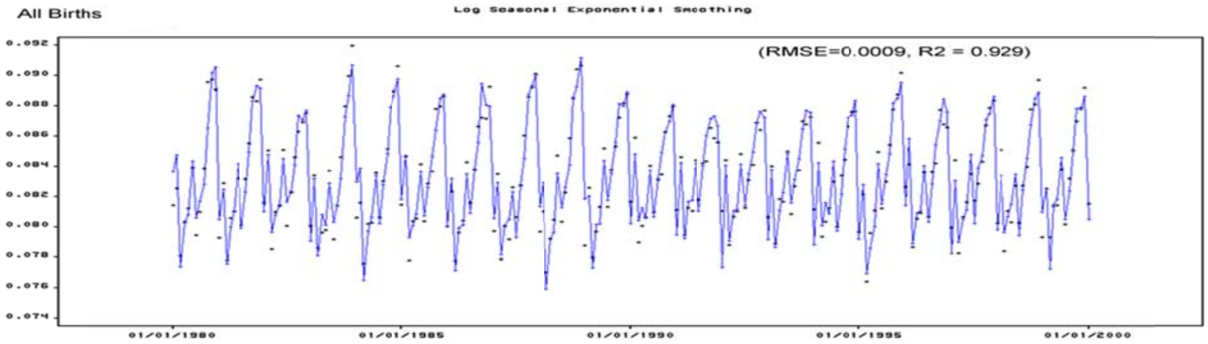
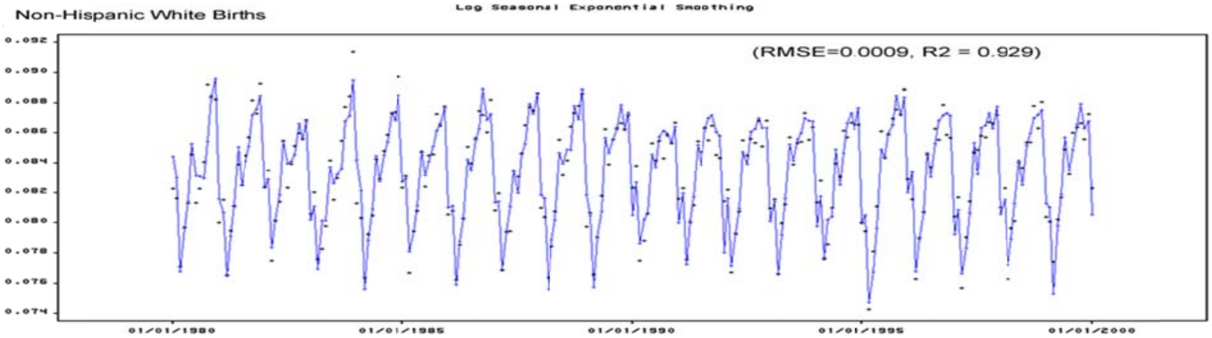
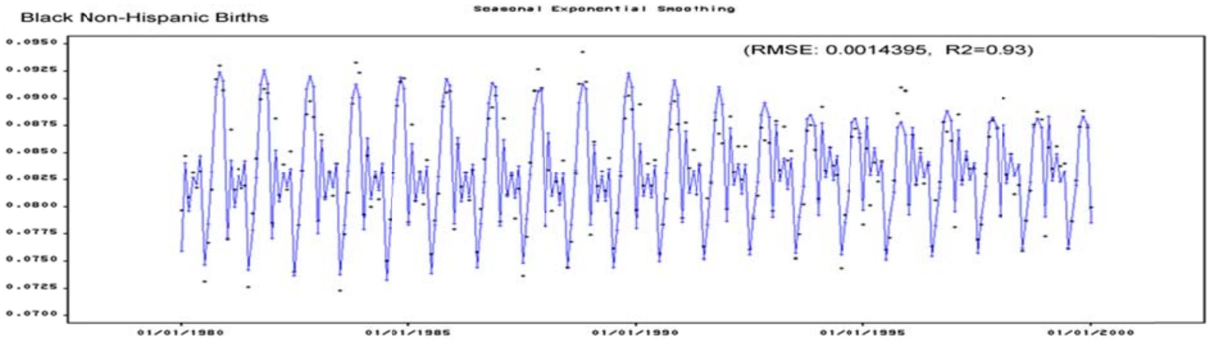


Figure 57. Monthly consumer confidence index (CCI) and sex ratio lagged to conception month, non-Hispanic white births 1979–2001, US large counties.







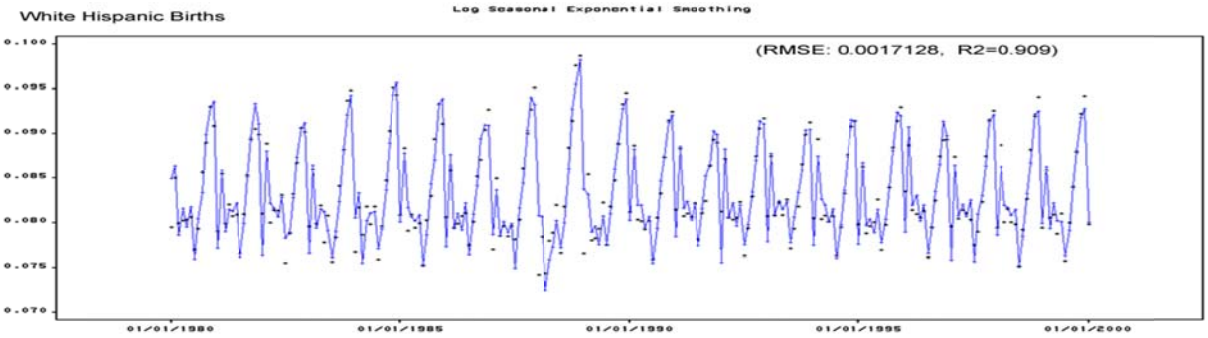


Figure 58. Smoothed monthly birth rates lagged to conception month, selected population groups, US large counties, 1979–2001 births.

The monthly variation in birth rate for non-Hispanic blacks and White Hispanic is highly correlated ($r_{pearson}$=0.85, p<0.0001), more so than are that of non-Hispanic whites and non-Hispanic blacks ($r_{pearson=}$0.439, p<0.0001) or non-Hispanic whites and Hispanic whites ($r_{pearson=}$0.655, p<0.0001). This can be seen more readily in a detail of the monthly birth rates for non-Hispanic white births, non-Hispanic black births, and Hispanic white births for January 1979 to December 1985 (Figure 59).

The seasonal conception birth rates for non-Hispanic whites show a greater trough in spring and a lesser peak in summer compared to the two other groups. These patterns invite cultural explanation, such as lack of access to air conditioning (e.g., Seiver 1989). However, they could also be explained by the different geographic distribution of the three groups, resulting in different seasonal exposures to climate variables. While 90 percent of Hispanics live in metro areas and have substantial populations in northern gateway cities like New York and Chicago, they are even larger proportions of the population of low latitude zone gateway cities of Miami, Houston and Los Angeles. They also make up 10 percent or more of the population in a majority of counties in the southwest US. In the 403 study counties, 74.2 of the births to Hispanic mothers occur in the low latitude half of the US.

Throughout this period, blacks continued to be concentrated in the south; in 2002, 55.3 percent lived in the South, compared to the West, Northeast, and Midwest; 59.5 percent of non-Hispanic black births in the 403 county study data occur in low latitudes. A relatively greater proportion of non-Hispanic white births occur in northern latitudes than do those of the two other groups (64.7 percent). I have already shown that relatively more non-Hispanic white births occur in northern latitudes or higher elevation regions during the summer, while relatively more births occur in southern latitudes during the winter. Although I cannot map this relationship coherently using the dispersed 403 counties used for the 1979–2001 study period, it can readily be seen by plotting the mean latitude of births by month, using the climate division centroid in which the birth occurred (Figure 60). The mean value of the monthly temperature lagged by one month (Mean Temp-1) is also displayed to show that the mean latitude of summer and fall births is higher than that of winter and spring births. This aggregated temperature measure is significantly positively correlated to the mean latitude of births ($r_{pearson}$=0.655, p<0.0001).

This figure reinforces studies such of Seiver 1985 and Rosenberg 1966 that show that seasonal variation of births differs geographically, and agrees with my geographic dataset seasonal preference smoothing maps showing that summer conceptions are more preferred at higher latitudes than lower ones, and that winter conceptions more preferred at lower latitudes than higher ones. Roenneberg and Aschoff (1990b) found in their global historical study of fertility that in regions with cold winters and moderate summers, conceptions positively correlate with temperature increases; while in regions at or near the equator, this correlation is negative, a pattern that can also be seen in the latitudinal seasonal preference for conception in US births.

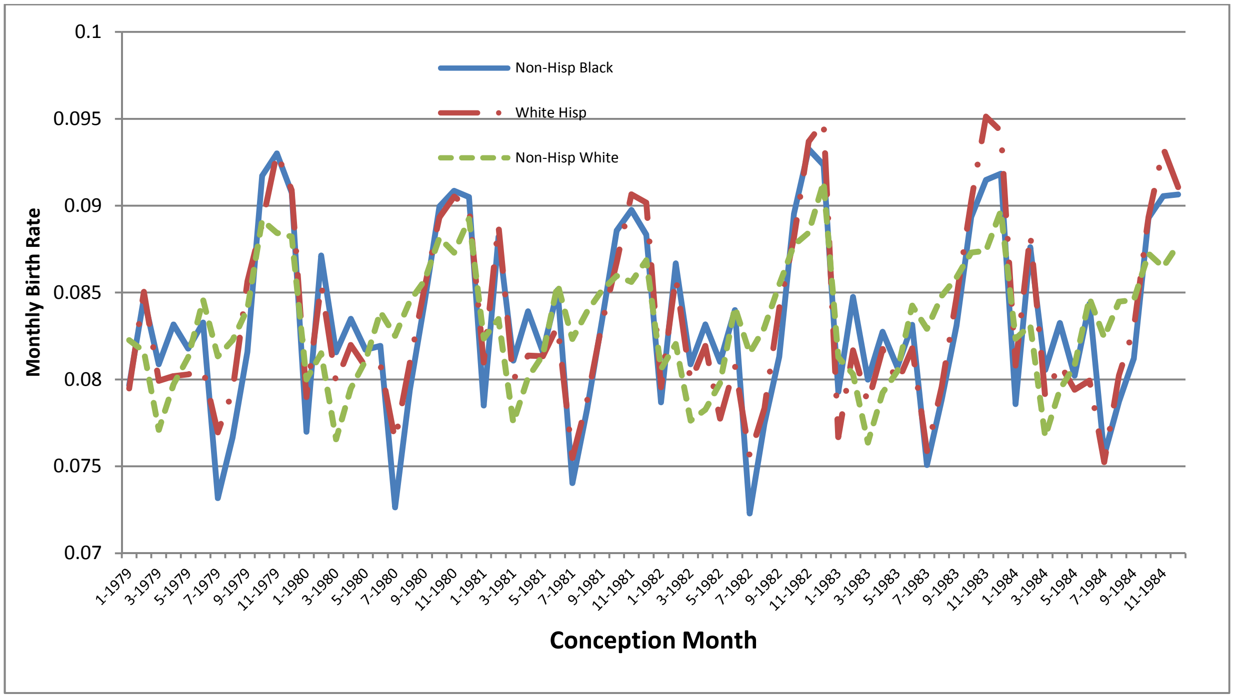


Figure 59. Monthly birth rates for non-Hispanic white, non-Hispanic black, and Hispanic whites lagged to month of conception, US large counties, 1979–1985.

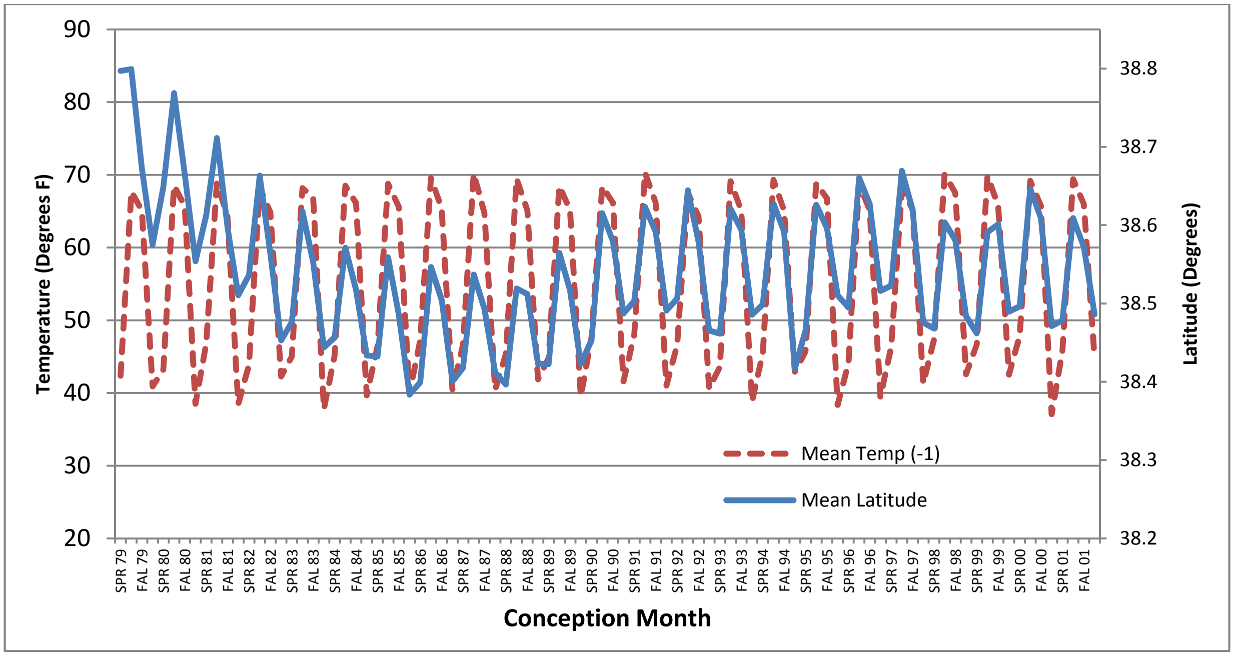


Figure 60. Mean latitude of non-Hispanic births by season of conception and mean seasonal temperature lagged by one month, US large counties, Spring 1979 to Winter 2001.

I have shown that a similar but more complex and less pronounced latitudinal seasonal pattern exists for conception of males. I have also shown that temperature in the month before conception is a significant explanatory variable for the gender of the child conceived. However, my exploratory analysis of the seasonal and geographic variation of this factor suggests that while warmer, lower latitude states have higher overall sex ratios, they have lower sex ratios in summer and fall relative to winter and spring than do conceptions in higher US latitudes. As I showed in my geographic weighted regression analysis of 1979–1988 births, summer conception of non-Hispanic white males are favored in higher latitudes relative to the lower latitudes, although the overall SRB of the low latitude zone is higher. Therefore, as for conception rates, the association between temperature and sex ratio at birth is dependent on both season and latitude.

The seasonality of sex ratio at conception I found in 1979–1988 births using the SAS time series forecasting analysis is also present in 1979–2001 births for the overall population (log seasonal exponential smoothing) and for non-Hispanic births (seasonal exponential smoothing)

(Figure 61). Seasonality was also detected in the spectral density analysis of sex ratio at conception for all births (Figure 62) and for non-Hispanic white births (the spectral density pattern is similar to that for all births and is not presented here).

No seasonality was found in the sex ratio of Hispanic births or non-Hispanic black births using this method. Because the geographic distribution of non-Hispanic whites results in different birth rate patterns than those of Hispanic whites, it is not unexpected that seasonal patterns of sex ratio differ also among these groups, as they do for the seasonal patterns of birth rates for these groups. James 1984 concluded that the seasonality of black SRB is synchronous with that of white SRB when aggregated across the US. However, I did not attempt a geographic and spatial variation of Hispanic and non-Hispanic births in this study.

The sex ratio for both non-Hispanic whites and Hispanic whites can be seen to decline over this period, although a seasonal pattern of SRB variation is not evident in the Hispanic groups. The lack of seasonality or pattern of decline in non-Hispanic black births may be related to their different geographic distribution compared to non-Hispanic whites, combined with countervailing improvements in prenatal health care during this period, as suggested by Davis et al. (2007), or other cultural practices or economic conditions not accounted for in previous studies.

Further, the lack of significant high correlation between variations in birth rate and sex ratio at conception may be due to the fact that birth rate is tied to the seasonal variation in daylength at different latitudes, while sex ratio is tied to environmental conditions that have greater variation. Helle et al. (2008) found that while annual values of sex ratio and temperature were associated in historic Sami populations, birth rate and temperature were not. They speculated that sex ratio at birth may be “a more environmentally sensitive component of female reproduction than fecundity per se.”

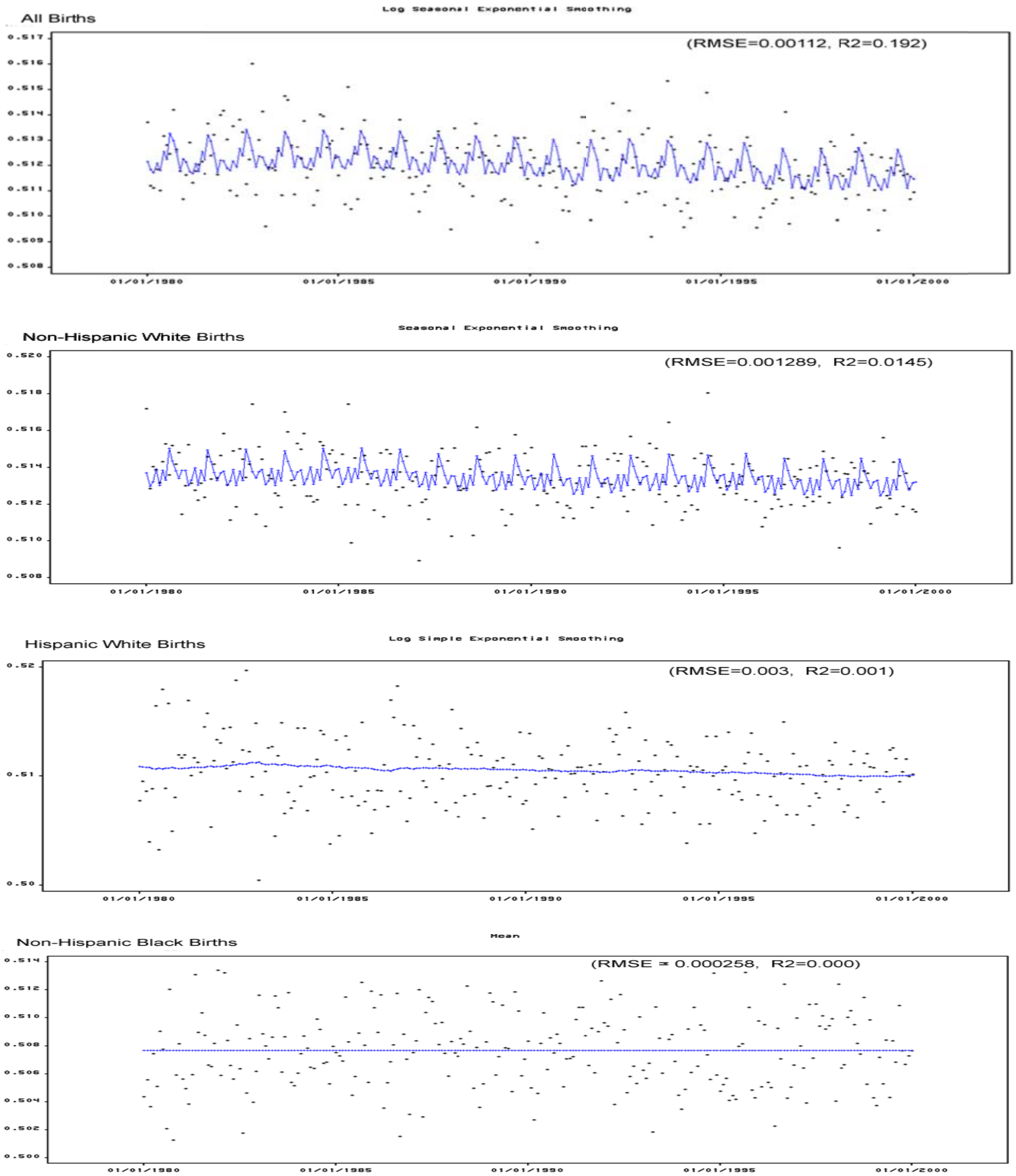


Figure 61. Smoothed monthly sex ratio lagged to month of conception, selected population groups, US large counties, 1979–2001 births. After adjustment for autocorrelation and trends, seasonal models were fit for overall US births and non-Hispanic births. A simple exponential smoothing model accounted for the variation in Hispanic white births. No patterns were found in SR non-Hispanic black births so a simple mean was selected as the best forecasting model.

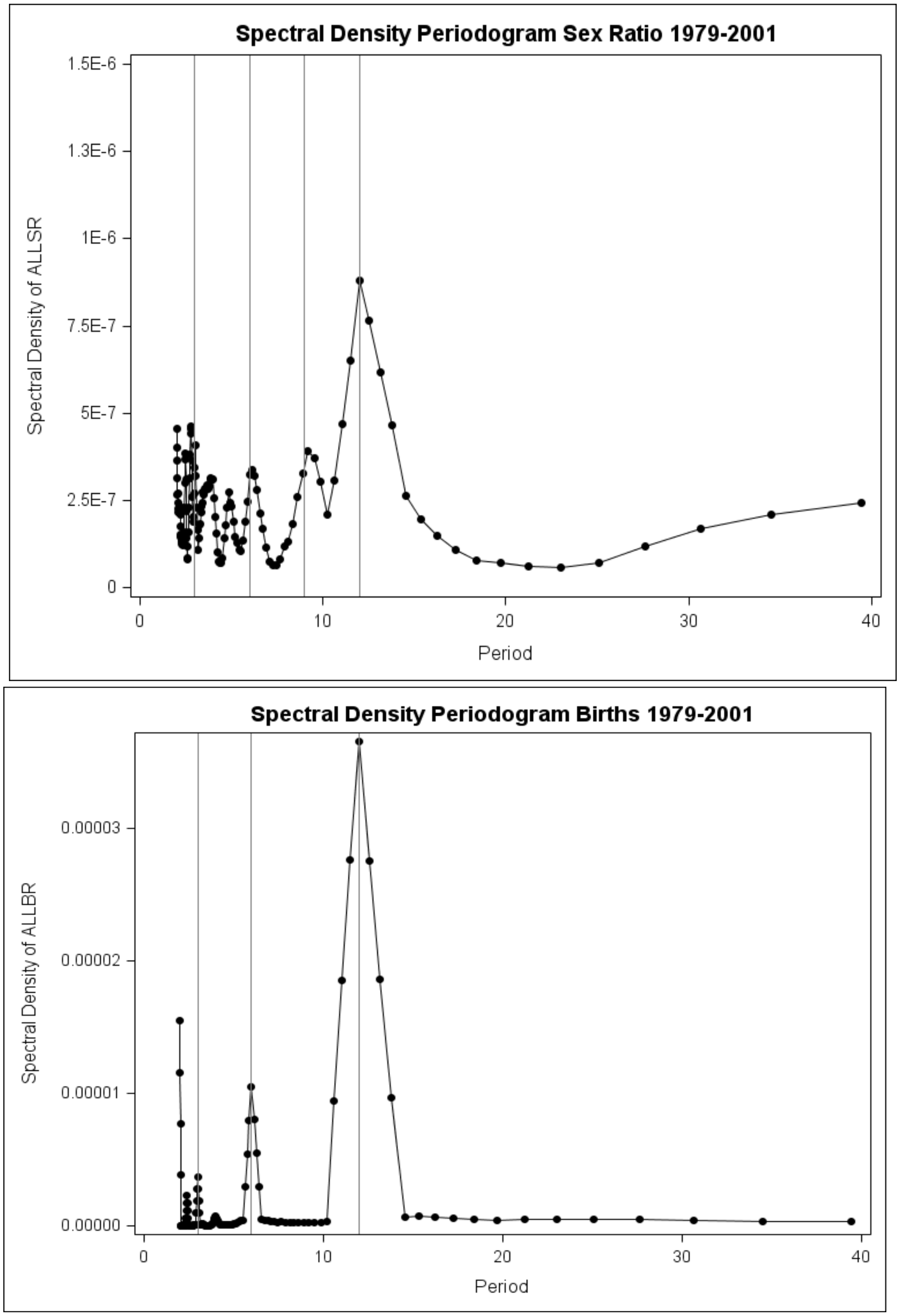


Figure 62. Plot of sex ratio at conception (top) and conception birth rate (bottom) spectral density estimate by number of monthly periods for estimated conception month, All Births US large counties, 1979–2001. Vertical reference lines drawn at 3, 6, 9, and 12 periods for sex ratio plot and at 3, 6, and 12 periods for birth rate plot.

The precise rhythm of the seasonal birth rate may represent an evolutionarily stable strategy (ESS) in terms of the game theory expressions of Maynard Smith and Price (1973). The agreement of the human species to reproduce at an approximately 1:1 sex ratio is, for example, an ESS. I have shown that the US seasonal birth rate varies by latitude, but within broad latitudinal regimes is remarkably stable. At various temperature and daylength regimes defined by latitude, there is, in theory, an optimum seasonal birth rate to which all members of the species subscribe as a strategy against competing species. Even in the face of climate changes, this pattern would be slow to change, since it represents a long history of successful outcomes in the form of surviving offspring.

However, individuals developing reproductive strategies within this temperature and daylight regime may respond to immediate variations in environmental conditions by varying the sex of their offspring (Trivers and Willard 1973). Parents in poor conditions or parents reproducing in poor environmental conditions will favor the production of females. The decline of sex ratio of the US population over the study period may be an expression of this mechanism, signaling that environmental conditions may have worsened over the period. I have shown that this decline is present even when social, economic and biological factors postulated to influence sex ratio at birth have been considered.

One of the most significant environmental factors for US populations during the study period is climate change, resulting in a temperature increases in US regional climates. The study period of 1979 to 2002 (for conceptions occurring 1979–2001) encompasses the beginning of the consensus that average surface temperatures were increasing globally and recent warm years that are among the highest recorded in US climate records to date. The positive association of temperature and sex ratio lagged to conception I have shown suggests that, in general, increasing warm trends should be associated with a corresponding increase in the proportion of male births. However, as Figure 63 shows, annual mean temperature for the United States has increased since 1979 while SRB has decreased. In the mid 1990s, annual mean temperature began exceeding the annual average of 53.51 degrees F for the period 1979 to 2008. The annual 1979–2008 temperature trend is an increase of 0.58 degrees per decade. The mean annual values of SRB and mean temperature for this period are negatively correlated

($r_{pearson}$=-0.46,p=0.009), whereas, for example, Helle et al. (2008) found that warm years among historical Sami populations corresponded to an above average male-biased sex ratio.

Despite the relationship between annual SRB and mean annual temperatures for US births, temperature in the month before conception appears to be significantly positively correlated with monthly rates of male conception during the 1979–2001 period. For the monthly sex ratio values in this population for 1979–2001, a cross-correlation of conception sex ratio and temperature in month before conception (BTMP) has the highest value correlation value (0.19) of any of the 24 lagged periods of conception sex ratio and B_TMP, using the SAS ARIMA cross-correlation method (Figure 64). A similar cross-correlation with the daylength in the month before conception (B_DAYL) is also displayed to show that the seasonal pattern of sex ratio at conception is more closely associated with changes in temperature in the preceding month than it is with daylength in the preceding month.

To explore this relationship further, I constructed a preliminary logistic regression model of 1979–2001 non-Hispanic white births using the same independent variables as I used for the logistic model developed for the 1979–1988 data: temperature in the month before conception (B_TMP), daylength in the month before conception, gestation period (normal, preterm, postterm), plurality, and parity. I added an additional term, conception year (CYEAR), to see if a significant decline in sex ratio was present when these other factors were considered. The BTMP variable is treated as a continuous variable in this model, rather than as a class variable with ranges, but its influence is assessed in 10 degree (F) units. This altered model returns similar results for equivalent variables in the 1979–1988 geographic dataset model, with expected relative impacts and influence direction for gestation, parity, plurality, and BTMP, and all variables are significant. In addition, conception year is significantly negatively correlated to the probability of a male birth, confirming a decline in SRB documented in other studies (Table 17). However, the hours of daylength before conception is not significant in this model as it was in the earlier one; I had suggested that this variable was a proxy for both seasonal and latitudinal variation in the 1979–1988 model. Further, this model fails the Hosmer Lemeshow goodness of fit test with a significant response, indicating that it does not fit the data well.

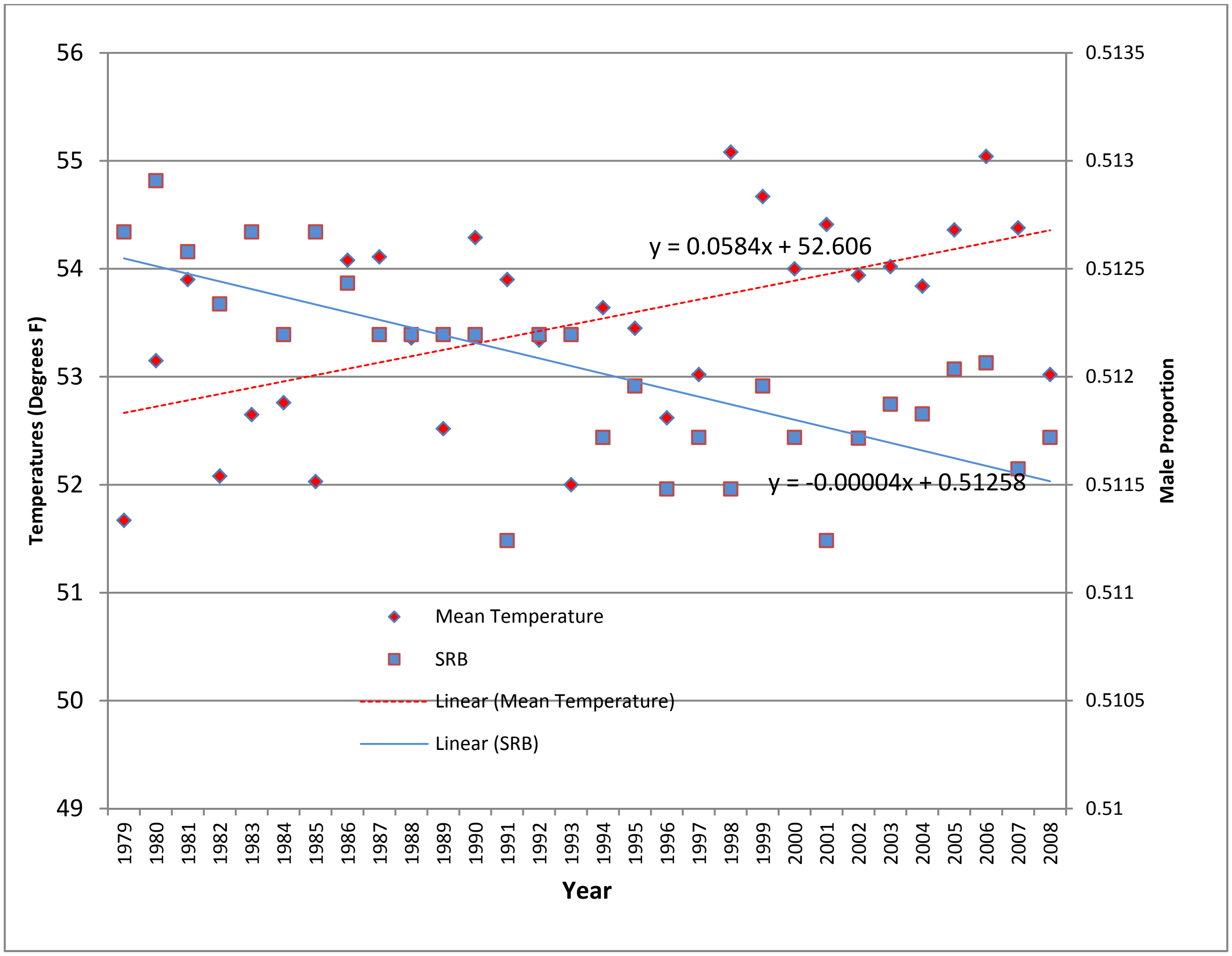
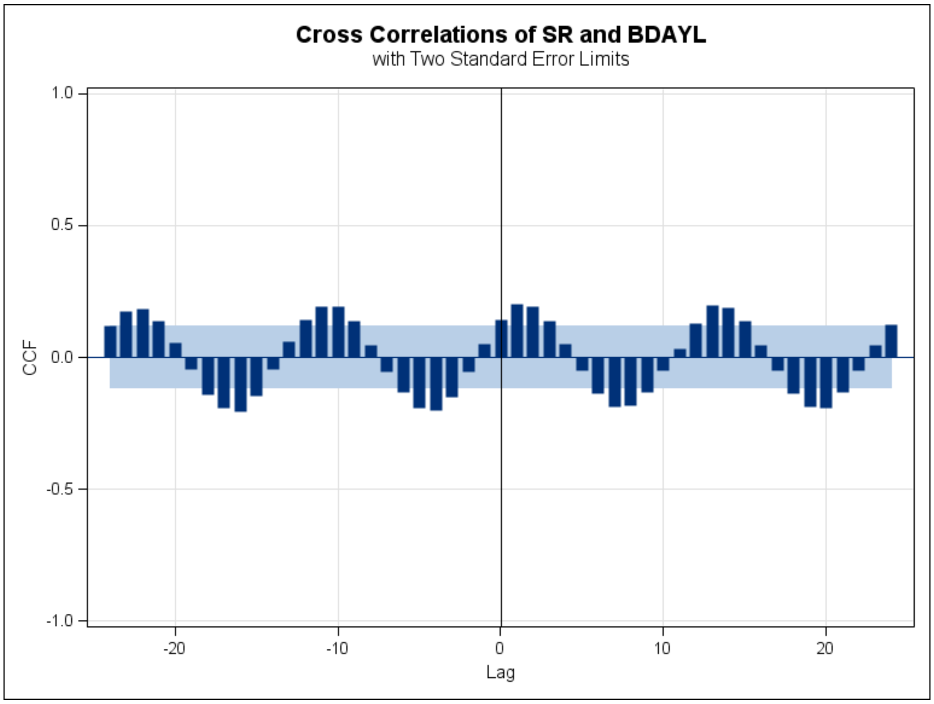


Figure 63. Average annual US temperature and annual sex ratio at birth, 1979–2008 (NCHS 2011, NOAA 2011).



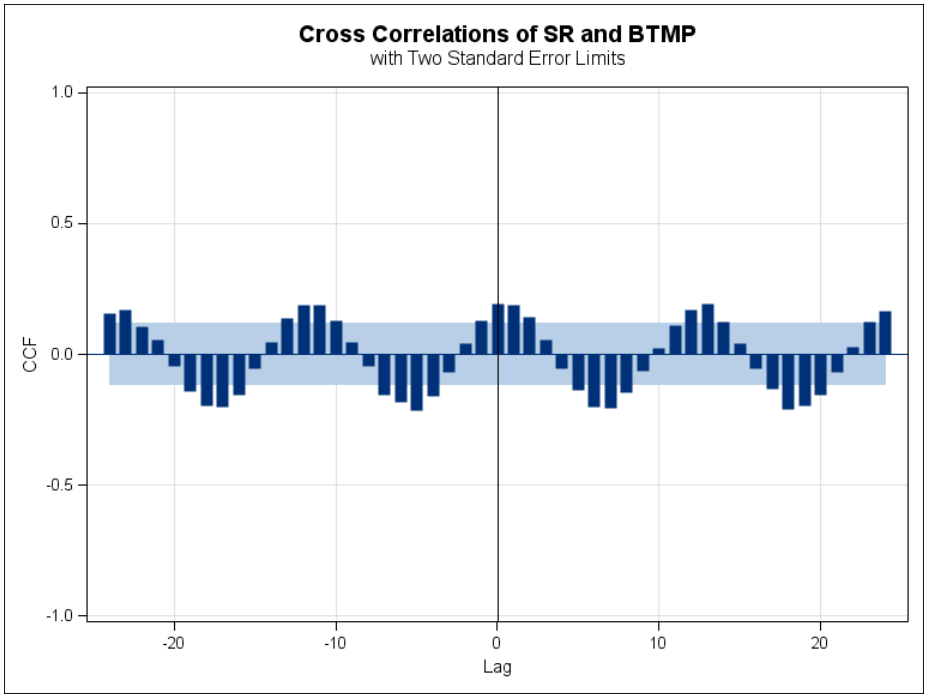


Figure 64. Cross-correlation tabulation of sex ratio lagged to month of conception and daylength in month before conception (BDAYL) and temperature in month before conception (BTMP), lags for 24 months before (positive values) and 24 months after (negative values), non-Hispanic white births, US large counties, January 1979 to December 2001.

Table 17. Maximum likelihood estimates of parameters for preliminary model of selected parameters for non-Hispanic white births conceived Jan 1979–Dec 2011, US large counties, with likelihood of male child as the model estimated.

Parameter	Estimate	Std. Err.	Wald Chi-Square	Pr > ChiSq
Intercept	1.0076	0.1104	83.3338	<.0001
CYEAR	-0.00059	0.000055	114.8548	<.0001
Gestation (Normal)	0.0583	0.00114	2617.9808	<.0001
Gestation (PreTerm)	0.1872	0.00165	12900.9377	<.0001
B_TMP (Deg F. Units of 10)	0.000088	0.000032	7.633	0.0057
Parity (firstborn)	0.00669	0.000913	53.6319	<.0001
Parity (secondborn)	0.00414	0.000954	18.8704	<.0001
Plurality (Singleton)	0.1541	0.00925	277.4689	<.0001
Plurality (Twins)	0.0617	0.00945	42.6813	<.0001
BDAYLENGTH (Hours)	-0.0001	0.000291	0.1296	0.7188

While confirming a decline in the sex ratio and the significant positive correlation of temperature with the likelihood of conceiving males, this model does not provide any insights into how the relationship of temperature and sex ratio might have changed during the study period, nor does it suggest any other factors that might be associated with the decline of SRB. To gain additional perspective, I examined sex ratio trends by grouping birth data into three approximately equal time periods: 1979–1985 (7 years); 1986–1993 (8 years); and 1994–2001(8 years). I also divided births by high and low latitudes within these periods using the previously described method, although the mid latitude zone from the previous chapter is merged into the low latitude category to provide nearly equal samples in the high and low latitude zones. Using estimated month of conception, sex ratio of all non-Hispanic white births significantly decreased for each successive period, based on Pearson chi-square and Mantel-Haenszel chi-square (Table 18).

Patterns of difference are similar among groups, with an approximately 0.08 percent decrease from the first period to the last. High latitude sex ratios are lower than low latitude sex ratios in each period, but not significantly, based on chi-square tests (1985: χ^2=2.65, p=0.10; 1993: χ^2=1.43, p=0.23; 2001: χ^2=2.83, p=0.09). This table analysis confirms that a decline in sex ratio at birth for non-Hispanic white births has been continuous over the study period and appears to have impacted births in both high and low latitudes. If seasonality persists in the sex ratio and is associated with temperature, have patterns of seasonality for this population changed during the study period in these latitude zones? A broad comparison of monthly rates and three-month moving average trendlines from the eight years at the beginning of the study period (1979–1986) with the eight years at the end (1994–2001) shows that the peak of sex ratio is considerably diminished in both high and low latitude births (Figure 65). This truncation of peaks is more pronounced in low latitudes than higher ones. In addition, the structure of the circannual rhythm is much less distinct in the latter period for the high latitude zone. The peak of high latitude sex ratio at conception occurs earlier in the year in the latter period than in the earlier period. A more detailed analysis of changes in seasonal structure between the two zones is shown in Figure 66, which compares seasonal sex ratio at conception for each of the three time periods I described in Table 18.

Table 18. Pearson chi-square and Mantel-Haenszel tests for sex ratio at conception by study periods ending in 1985, 1993, and 2001 for total non-Hispanic births and by high and low latitude, US large counties, 1979–2001.

All NWH

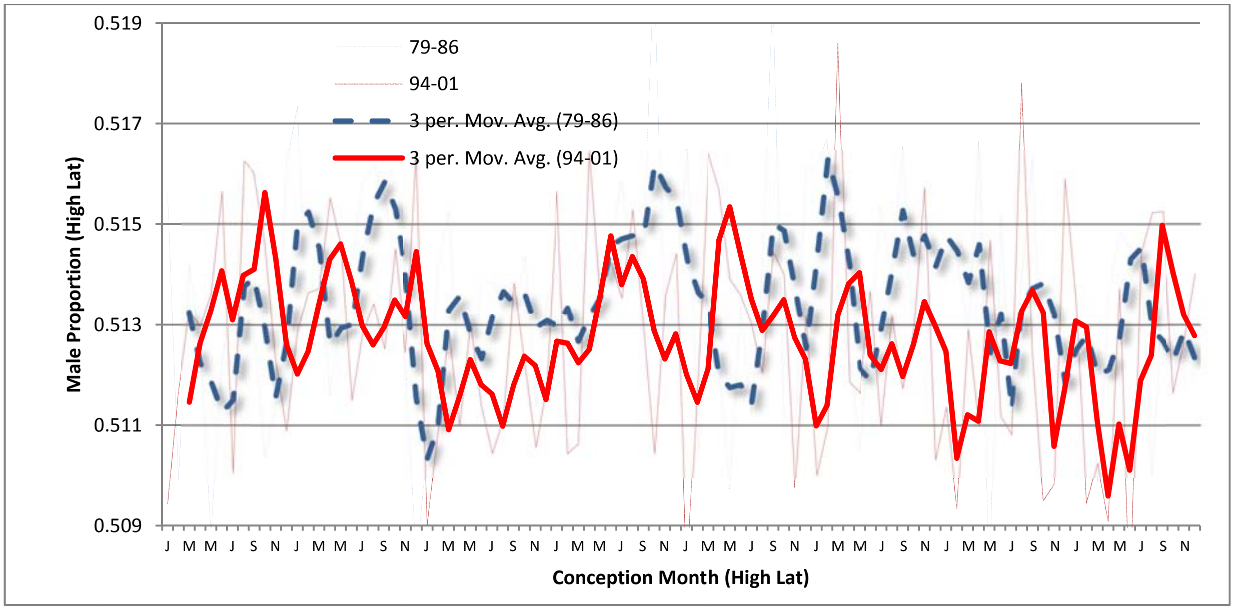
	Period Ending			
Sex	**1985**	**1993**	**2001**	Total
Boys (Freq)	5889739	6915840	6037770	18843349
Boys (Pct)	51.38%	51.33%	51.30%	
Girls (Freq)	5574346	6557464	5732690	17864500
Girls (Pct)	48.62%	48.67%	48.70%	
Total	11464085	13473304	11770460	36707849
	Df	Val	Prob	
Chi Square	2	14.8303	0.0006	
Mantel-Haenszel Chi-Square	1	14.7149	0.0001	

Low Latitude NWH

	Period Ending			
Sex	**1985**	**1993**	**2001**	Total
Boys (Freq)	2843782	3432892	2966736	9243410
Boys (Pct)	51.40%	51.35%	51.32%	
Girls (Freq)	2688815	3252865	2814012	8755692
Girls (Pct)	48.60%	48.65%	48.68%	
Total	5532597	6685757	5780748	17999102
	Df	Val	Prob	
Chi Square	2	7.4628	0.0240	
Mantel-Haenszel Chi-Square	1	7.1148	0.0076	

High Latitude NWH

	Period Ending			
Sex	**1985**	**1993**	**2001**	Total
Boys (Freq)	3045957	3482948	3071034	9599939
Boys (Pct)	51.35%	51.31%	51.27%	
Girls (Freq)	2885531	3304599	2918678	9108808
Girls (Pct)	48.65%	48.69%	48.73%	
Total	5931488	6787547	5989712	18708747
	Df	Val	Prob	
Chi Square	2	7.7389	0.0209	
Mantel-Haenszel Chi-Square	1	7.7337	0.0054	



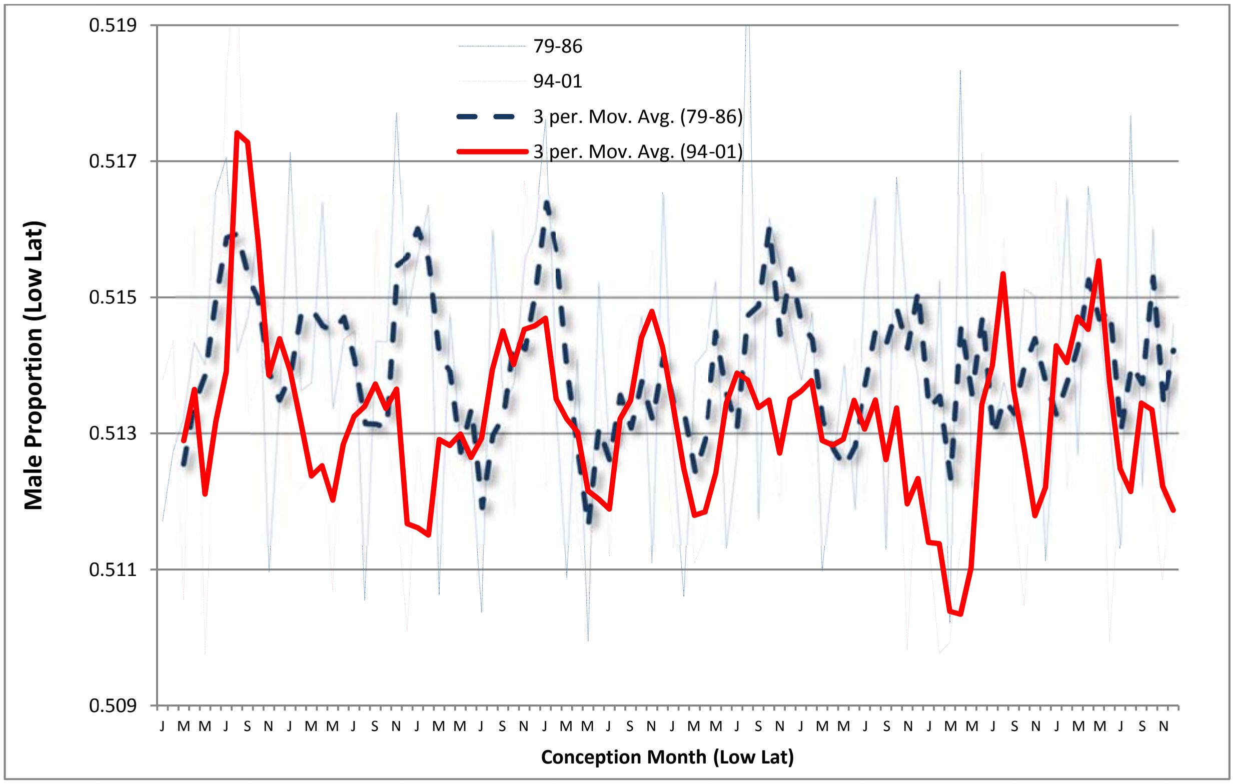


Figure 65. Monthly sex ratio at conception and three month moving average for period 1979–1986 compared to 1994–2001 period for high latititude (top) and low latitude (bottom) non-Hispanic white births. US large counties.

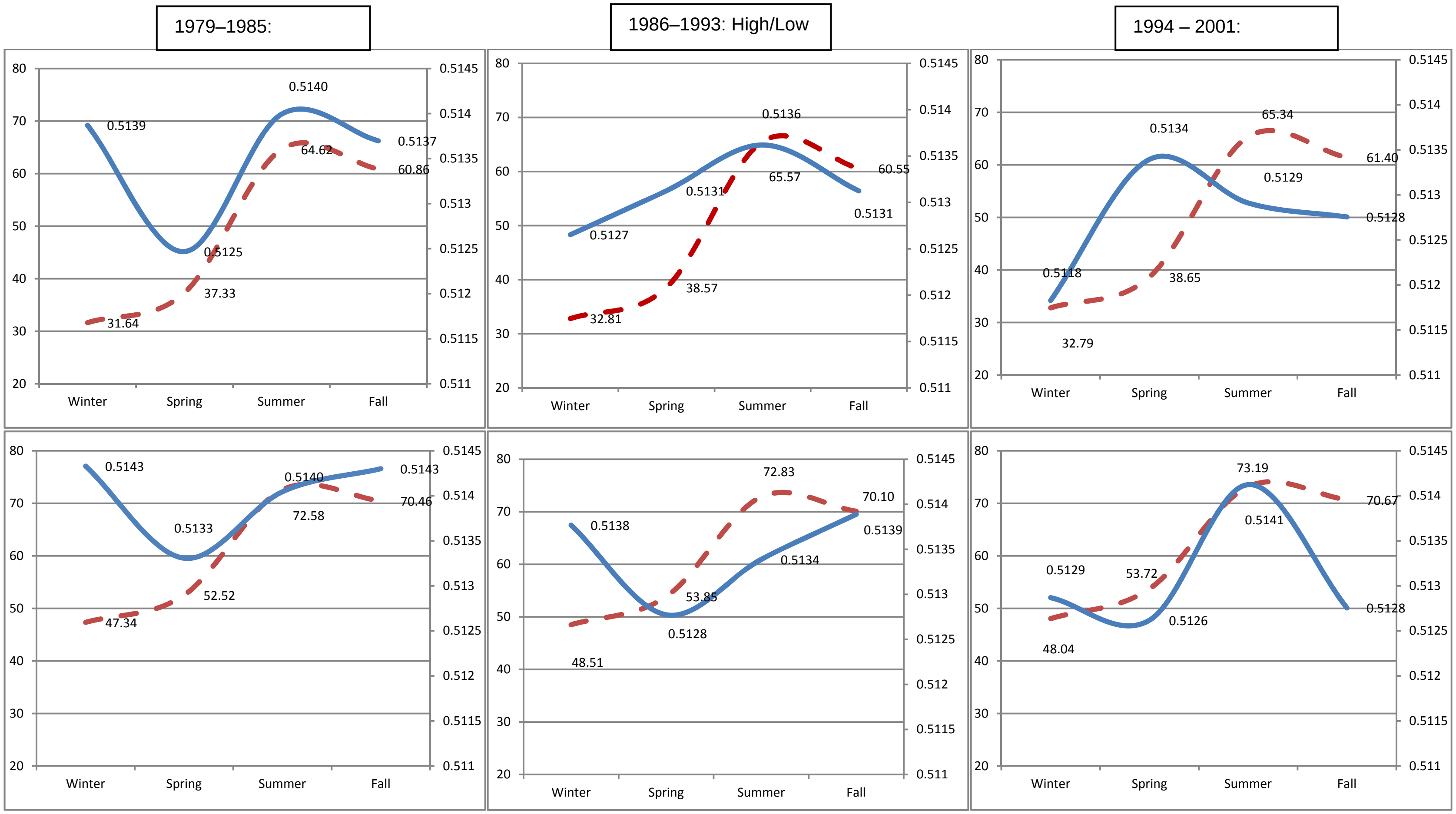


Figure 66. Sex ratio at conception by season and latitude zone for non-Hispanic, white births in US large counties for 1979–1985, 1986–1993, and 1994–2001. Sex ratio is solid line, temperature before conception is dashed line. An aggregate seasonal mean temperature in the month before conception (seasonal values lagged by one month) is also plotted for each of the six panels.

In the seasonal comparison of time periods shown in Figure 66, the scale for temperature and sex ratio is the same in all six panels. In general, there are sex ratio reductions in all seasons over the study period. There are also notable changes in seasonal pattern. For both high and low latitudes, there is relative reduction in the conception of rates of males in the winter compared to 1979–1985 period. The spring trough present in high and low latitude births in the 1979–1985 births has disappeared in the 1994–2001 births. In the high latitude zone, the peak conception season has moved to the spring.

A monthly aggregate of monthly SRB values for non-Hispanic births for these three periods shows this seasonal variation in more detail and compares them to changes in monthly birth rates over the same period. Monthly birth rates are expressed as percentage deviations from the mean monthly birth rate in the year in which the conception occurred. A third-order polynomial trend line is fit to birth rates and sex ratios for each period for visual comparison of trends. Birth rates in high latitudes (Figure 67) have similar patterns in all three periods, with the birth rate in the first five months of the year lower relative to the remainder of the year. However, over the three periods relatively few births occur in the spring relative to the remainder of the year. At the same time, the sex ratio conception peak shifts earlier, towards the spring. In the low latitude zone (Figure 68), births are also conceived at a relatively lower rate in the first five months of the year. However, June represents a brief minor peak, after which rates climb again through December. Over the three periods, there has been a flattening of the low spring, high fall conception trend, with notably large drops in the fall peak. Over the same period, sex ratio at conception has also flattened, with fall sex ratio conception rates much lower than in previous periods and the peak shifting towards the summer.

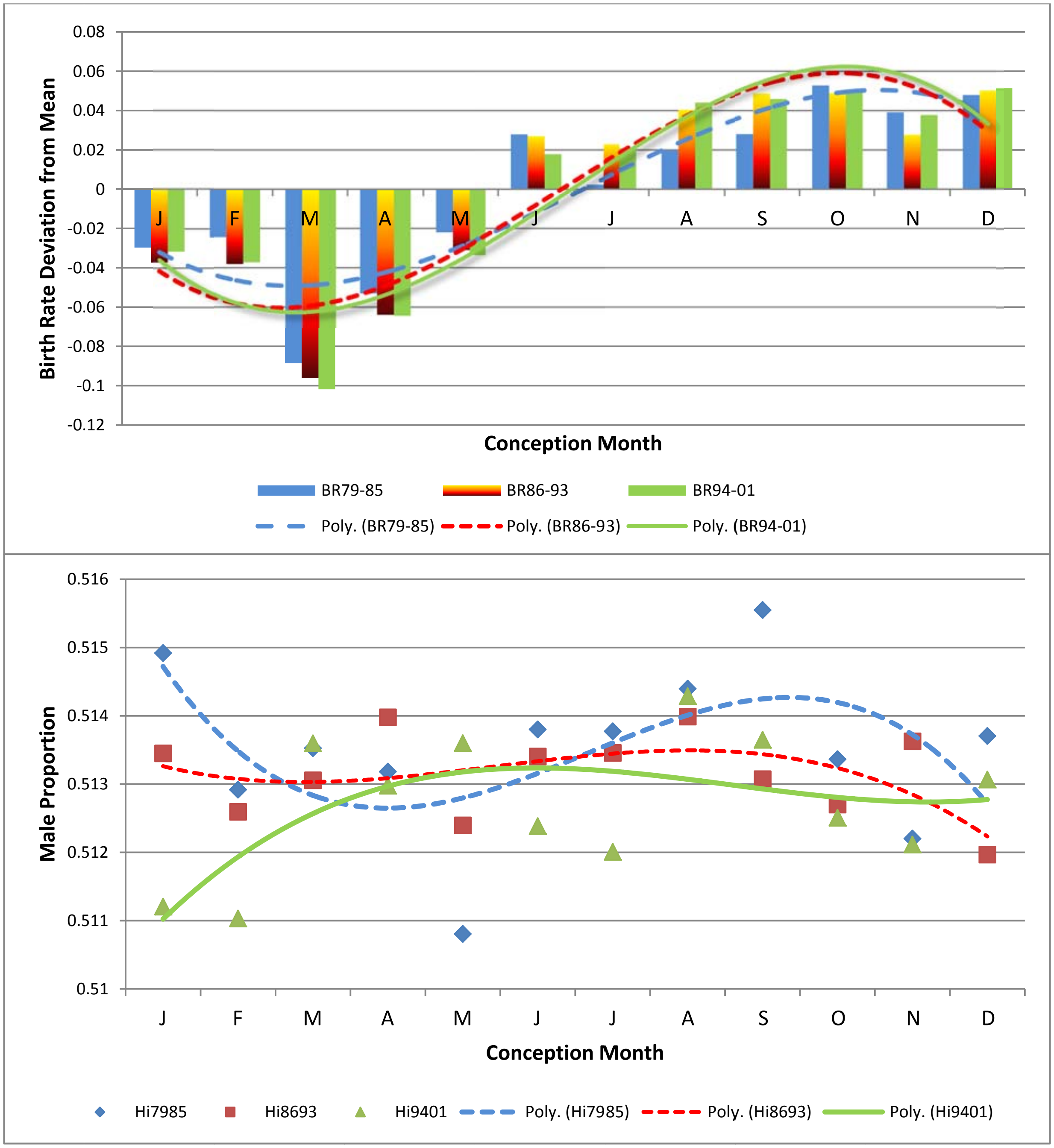
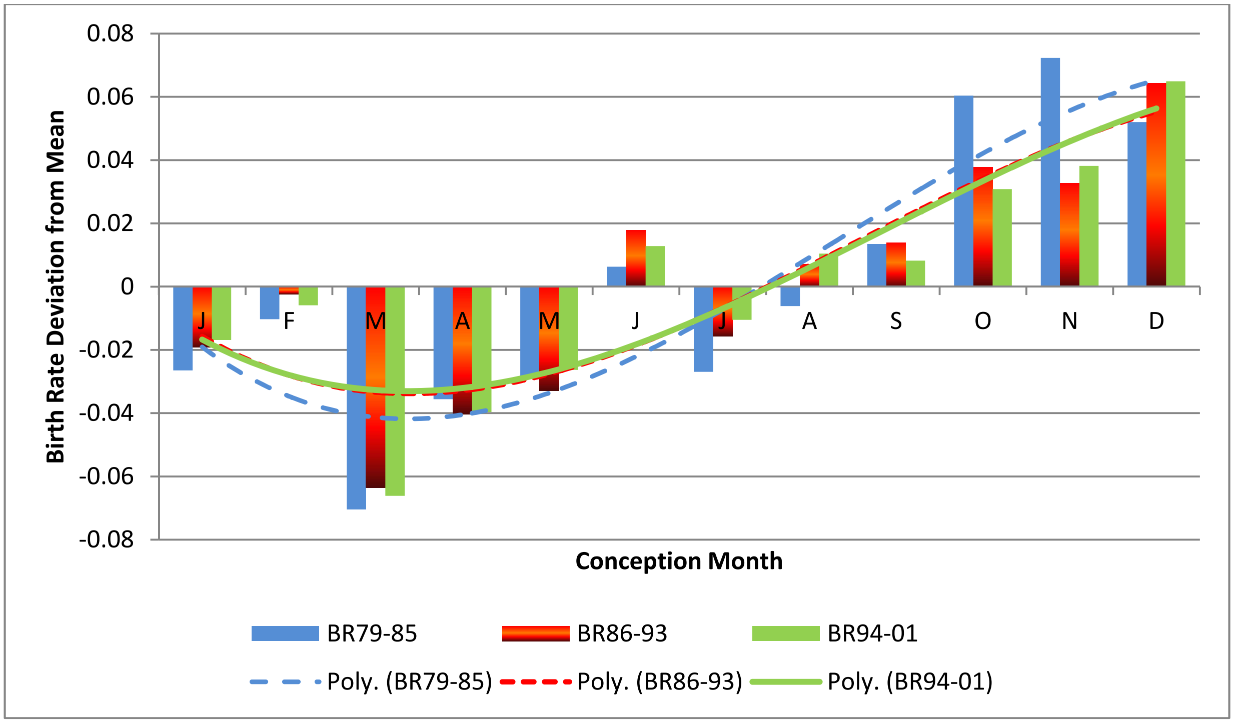


Figure 67. High latitude non-Hispanic white birth rate (top) and sex ratio at conception (bottom) by month for periods ending 1985, 1993, and 2001 for births in US large counties 1979–2001.



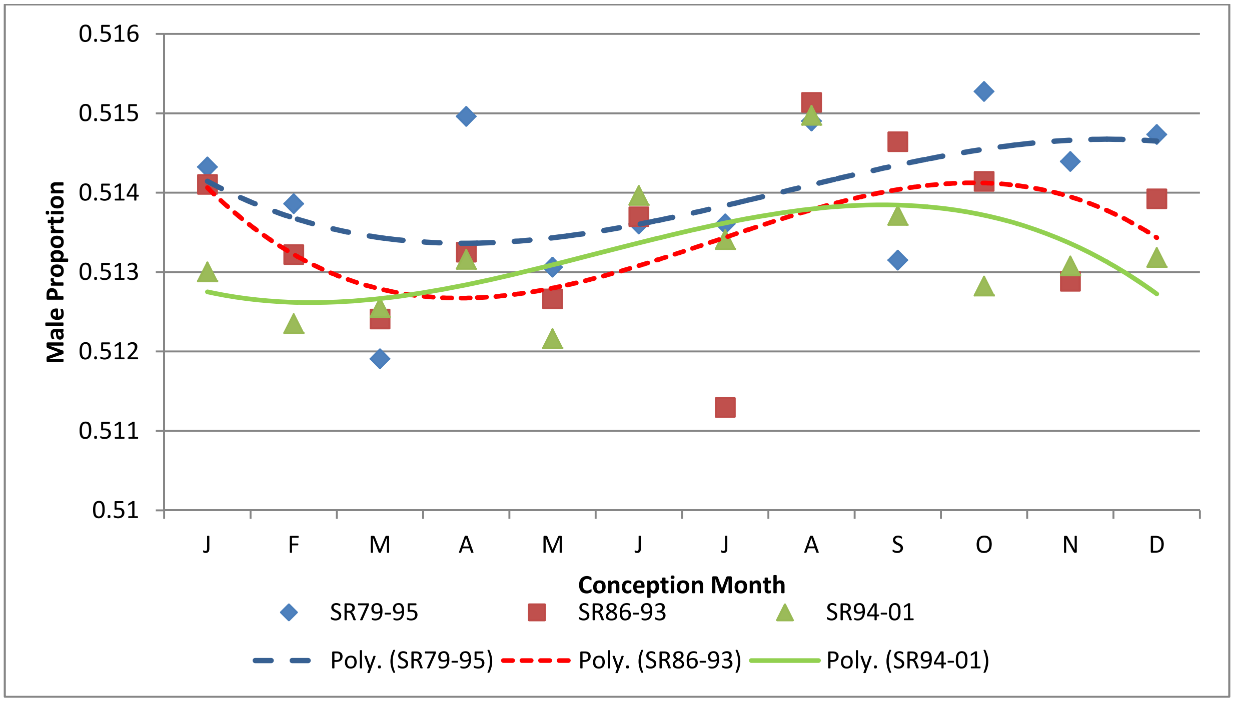


Figure 68. Low latitude non-Hispanic white birth rate (top) and sex ratio at conception (bottom) by month for periods ending 1985, 1993, and 2001 for births in US large counties 1979–2001.

Given the association I have demonstrated between pre-conception monthly temperature and sex ratio and the seasonality of birth rates and sex ratio, it is reasonable to associate change in seasonal sex ratio and birth patterns with increases in average monthly temperatures as a result of climate change. As I documented in the literature review, increases in average temperature during the study period have been documented in the US, but vary by season and region. As Figure 69 shows, the degree to which average temperatures have changed during the study period have distinct areas of concentration, using the 1971–2000 climate division average as the baseline to calculated average anomaly temperature values. The upper Midwest has experienced the greatest increases of temperature, while the extreme Southeast has cooled, using this baseline. In general, the Southeast has experienced a lesser increase in absolute temperatures than most of the high latitude zones of the US during this period. This may offer a partial explanation why seasonal sex ratio patterns have differed less from previous periods than have those for higher latitudes.

One of the clearest ecological consequences of climate change is an earlier onset of spring, along with associated changes in periodic plant and animal life cycle activities, that is, phenological events such as migration and flowering. Root et al. (2003), for example, found in a meta-analysis of 143 studies that most phenological events are occurring earlier in spring as a result of climate change induced temperature increases. The apparent recent spring-ward shift in the peak of human sex ratio at conception, especially at higher US latitudes, may be a part of this general ecological phenomenon.

A possible outcome of this shift would be to expose the seasonal pattern of peak and trough conception of males to different temperature and daylength relationships. Higher winter and spring temperatures and warmer summers in higher latitudes would also be expected to alter the pattern of summer preference for male conception in higher latitudes compared to lower latitudes in the US.

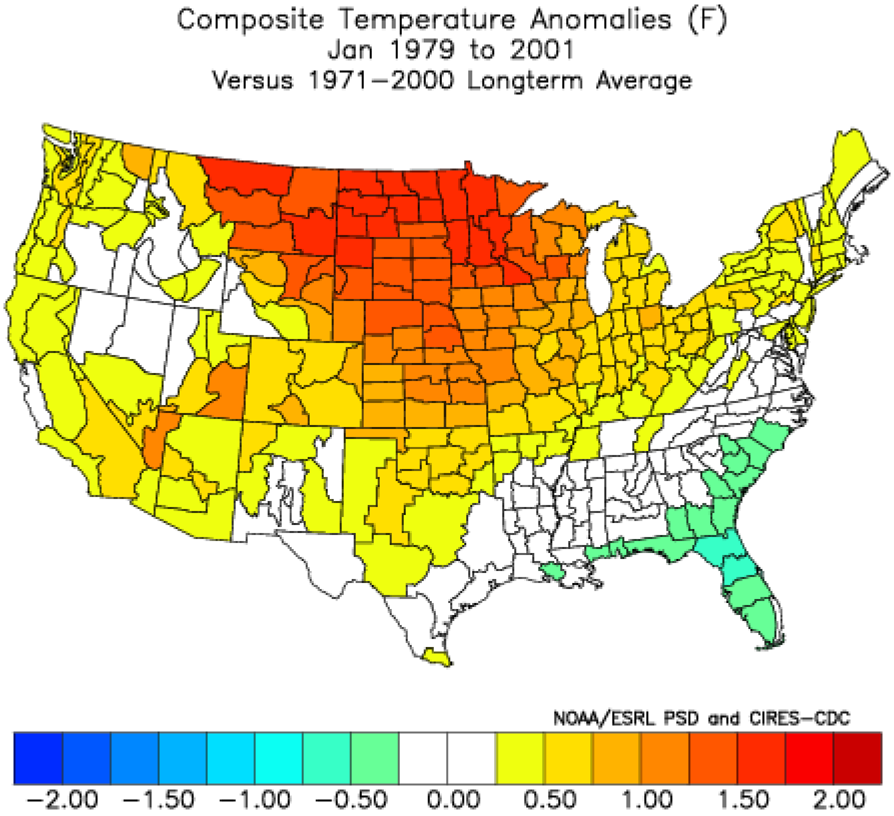


Figure 69. Temperature anomalies in degree F for climate divisions 1979–2001 based on 1971–2000 average (NOAA 2011).

Global Model of US Sex Ratio at Birth and Climate Change Association

The final statistical model in this study is a logistic regression of individual non-Hispanic births conceived between 1989 and 2000. Although this is a shorter time period than that which I have compiled data for, it reflects the concern for data quality expressed by Branum et al. (2009), who excluded NCHS data prior to 1981 based on goodness of fit criteria, and data prior to 1989 for analyses based on Hispanic ethnicity due to incomplete reporting by states. Also, as I noted in the previous methods chapter, 100 percent samples from all states were not recorded in NCHS data until 1985. Although I have argued that my use of Hispanic ethnicity reporting prior to that time did not materially affect the geographic and temporal analysis presented here, this later analysis period further assures that this factor is controlled. Using a conception year beginning in 1989, the year of the revised US standard birth certificate, represents births recorded in late 1989 and later. The selected model period of 1989 – 2001 also encompasses the period in which increased temperature effects began to be noted and within which hypothesized temperature related associations appear to be most concentrated.

The US SRB climate change model was fit in a similar manner as the geographic model for 1979–1988 study period. To assess the possible effects of local socioeconomic conditions I again included a value for infant mortality rate (IMR), per capita income (PCI), and percent below poverty level (PovLev). Because these were derived from single year values assembled in the City and County books (see Table 12) occurring towards the beginning and towards end of the model period, I distributed these two values to conception periods as shown in the table below.

Table 19. Assignment of county level socioeconomic variables by conception year.

Variable	Conception beginning	Conceptions ending
IMR90	Jan-90	Dec-94
IMR00	Jan-95	Dec-01
PCI90	Jan-90	Dec-95
PCI00	Jan-96	Dec-01
PovLev89	Jan-90	Dec-94
PovLev00	Jan-95	Dec-01

Because raw per capita incomes differed from the 1990 to 2000 tables, they were converted to standardized z values using the mean per capita income of 1990 and 2000, respectively. As an additional measure of economic wellbeing, I included monthly consumer confidence index values for each birth. I also considered maternal education as a proxy for personal economic status, although this variable has the largest number of missing values of any individual variable I consider.

Based on previous analysis, I considered a reduced set of climate variables from Table 1, including only temperature before (BTMP), during (TMP), and after (ATMP) the month of conception, cooling and heating degrees days for these three periods (CDD, BCDD, ACDD and BHDD, HDD, AHDD, respectively), and monthly precipitation in inches for these periods (BPCP, PCP, and APCP). Z-scores for temperature and precipitation compared to the baseline

1971 to 2000 period were also included (BPCPZ, PCPZ, APCPZ and BTMPZ, TMPZ, and ATMPZ, respectively). BDAYL, DAYL, and ADAYL values for hours of daylength were also included.

I also included the Monthly Bivariate ENSO Time Series (ENSO Ind) Index created by the Earth System Laboratory of NOAA as a long period measurement of the El-Nino/Southern Oscillation for research purposes (NOAA 2011). These values are standardized over the period and present positive and negative values to express the strength of El Nino and La Nina events, respectively. To an extent not fully understood, ENSO influences jet stream location and patterns of temperature and precipitation, including the frequency and intensity of severe weather. El Nino events occur every one to three to seven years and last about one year. One major El Nino event — 1997–1998 — occurred during the analysis period, the strongest such event recorded. During the 1989 to 2001 period, there is a small but significant correlation between SRB and the ENSO index ($r_{pearson}$=0.239, p=0.003). See the relative variation of these values in Figure 70.

Geographic variables considered include latitude of census division centroids (LAT), latitude zone (LATHALF: high or low), latitude zone (LATZONE: high, mid, or low), US energy climate zone (CLIMZONE: see Table 13), and US census division (CENSDIV). The initial model began with all non-Hispanic white births with no missing values for climate, economic, or geographic variables. I again assessed as baseline individual biological and cultural characteristics mother's age (MATAGE), birth order of the child (PARITY), plurality (PLURALITY), and socioeconomic and biological factors represented by the proxy gestation period (GW, by class of Preterm, Normal, PostTerm). Again, no data related to the father was included due to the large number of missing records for paternal information. Some of these characteristics have missing values and most were coded into classes for clarity of interpretation. Variables coded as class variables with a reference category are described in Table 20.

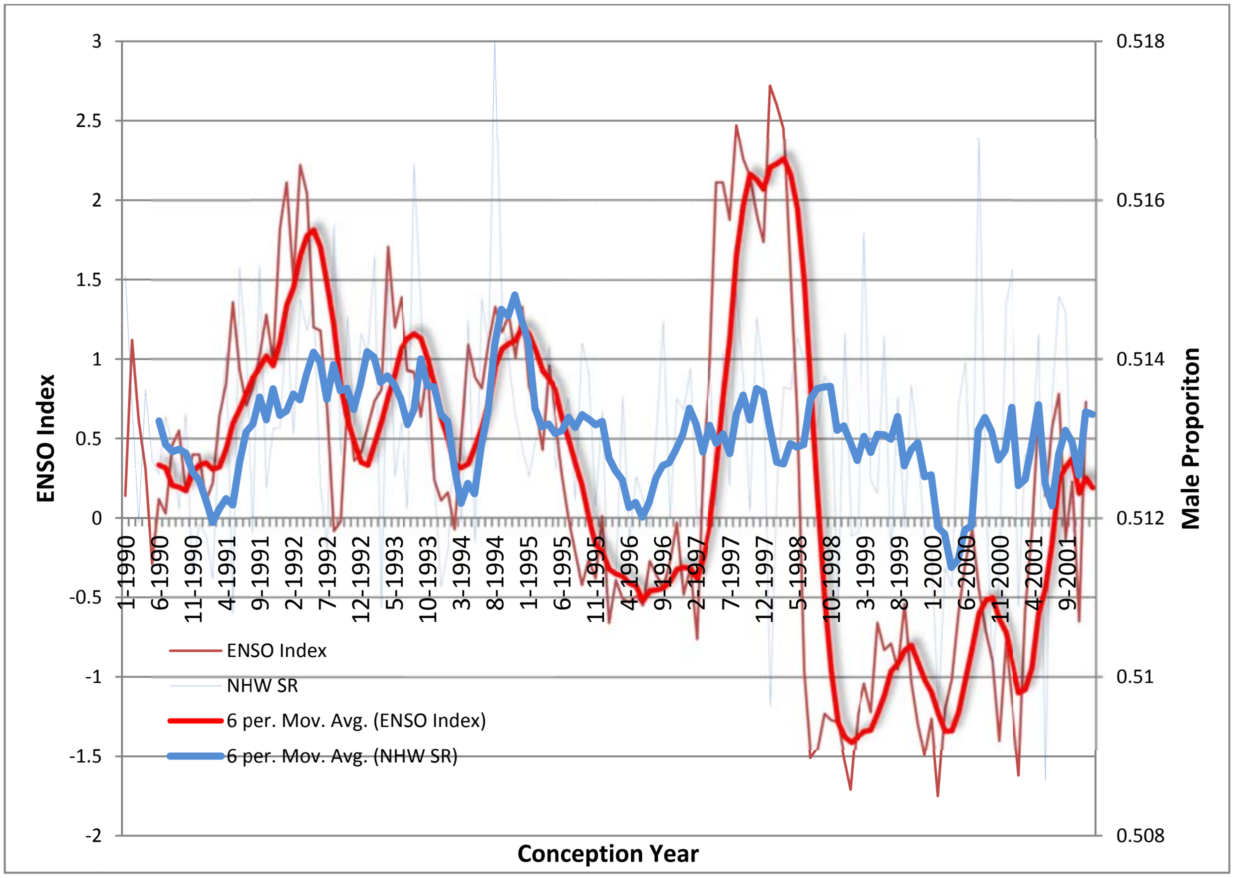


Figure 70. ENSO Monthly BEST index and non-Hispanic white births sex ratio lagged to conception monthly values, US large counties, 1989 to 2001, with three month moving average trendlines for both.

Table 20. Class variables and coding for 1989–2001 model. Class values with bold descriptions are reference variables.

Variable and Class Value	Description	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Maternal Age (MATAGE)					
1	<18 years	466256	2.34	466256	2.34
2	18 to 30 years	12051945	60.42	12518201	62.75
3	31–39 years	6965989	34.92	19484190	97.67
4	**Over 40 years**	463915	2.33	19948105	100
Gestation (GW)					
1	>=37 and <42	6346425	82.04	16346425	82.04
2	<37	1851593	9.29	18198018	91.34
3	**>=42**	1726263	8.66	19924281	100
Missing				23824	
Birth Order (PARITY)					
1	First born	8468846	42.6	8468846	42.6
2	Second born	6733363	33.87	15202209	76.47
3	**Third or greater**	4677255	23.53	19879464	100
Missing					68641
Plurality (PLURALITY)					
1	Singleton	19326962	96.89	19326962	96.89
2	Twins	580214	2.91	19907176	99.79
3	**Other multiple**	40929	0.19	19948105	100
Marital Status (MARITALSTAT)					
1	Married	16139340	80.91	16139340	80.91
2	**Unmarried**	3808765	19.09	19948105	100
Maternal Education (MATEDUC)					
1	Less than High school	2120938	10.87	2120938	10.87
2	High school	6158522	31.57	8279460	42.44
3	Some college	4744333	24.32	13023793	66.76
4	**Bachelors degree or higher**	6483264	33.24	19507057	100
Missing				441048	

The model was again fit using the SAS LOGISTIC procedure, modeling the probability that birth would be a male, using the Fisher scoring method of estimating the regression parameters. Initial model runs used backwards and stepwise selection procedure to reduce the total number of variables, specifying a significance level of 0.10 for entry into the model and 0.05 for retention. Thereafter, selection with a significance level of 0.05 was used to fit the model, based on a chi-squared distribution of the likelihood ratio of each independent variable. Parsimonious model selection and adequate goodness of fit were evaluated as described for the 1979–1988 model.

The fitted model used 19,948,105 observations and had satisfactory values for 2 LOG L ($p<0.0001$), AIC criterion, and Hosmer Lemeshow goodness of fit ($p=0.07$). Model results are reported on Table 21 and odds ratios plotted in Figure 71. The greatest variation in male birth likelihood is again associated with factors represented by the proxy length of gestation value. Factors present at the time of conception that lead to preterm births are highly associated with male births, compared to normal and postterm births. In this model, older mothers give birth to more females than do younger ones and singleton births have higher proportions of males than do multiple births.

Although maternal education has a high number of missing values, it is also a useful proxy of socioeconomic status. Difference in material education produces expected SRB variation values, showing that mothers who are high school graduates produce more sons in this model than do those with less than a high school education; in turn, those with some college or a bachelor’s degree or higher produce more sons than do those with lesser education.

Conception year has a significant negative association with sex ratio. Even with controls for this marker of decline, maternal age, personal economic condition (maternal education proxy) and gestation period, temperature in the month before conception is a significant positive influence on sex ratio at conception (BTMP)

Table 21. Maximum likelihood estimates of parameters for sex ratio and climate change model of selected parameters for non-Hispanic white births conceived 1989 to 2001. US large counties, with likelihood of male child as the model estimated.

Parameter	Class Code	Estimate	Std Err.	Chi-Square	Pr > ChiSq
Intercept		0.9806	0.2465	15.821	<.0001
CYEAR		-0.00059	0.000123	22.5204	<.0001
Gestation (Normal)	1	0.0657	0.00163	1619.92	<.0001
Gestation (Preterm)	2	0.1934	0.00221	7658.994	<.0001
TMPZ (Standard Temp Anomaly)		-0.00142	0.00045	9.9957	0.0016
BTMP (Temp Month Conception)		0.000058	0.000028	4.2241	0.0399
Mother Age (Less than 18)	1	0.021	0.00445	22.3083	<.0001
Mother Age (18-30)	2	0.00992	0.00306	10.5254	0.0012
Mother Age (30-39)	3	0.00603	0.00308	3.8433	0.0499
Maternal Education (High School)	2	0.00691	0.00171	16.2769	<.0001
Maternal Education (Some College)	3	0.00842	0.00179	22.1644	<.0001
Maternal Education (Bachelors or Greater)	4	0.0146	0.00177	68.4845	<.0001
Plurality (Singleton)	1	0.1506	0.0101	221.5898	<.0001
Plurality (Singleton)	2	0.0566	0.0104	29.8068	<.0001

Most importantly, this model also finds an additional climate term significant that was considered but not fit in the 1979–1988 model: the standardized temperature anomaly during the month of conception (TMPZ). High values for TMPZ indicate temperatures above the climate division mean temperature for the 1971–2000. Unlike BTMP, the association between TMPZ and sex ratio is negative.

No geographic distinctions were found significant in this model. To test the association between sex ratio and temperature deviation to geographic detail, I ran the model separately for births in the high latitude zone and those in the low latitude zone. The results were essentially the same for all variables, except that the temperature in month before conception (BTMPZ) is a significant explanatory variable and a better fit for a model of low latitude births than was TMPZ.

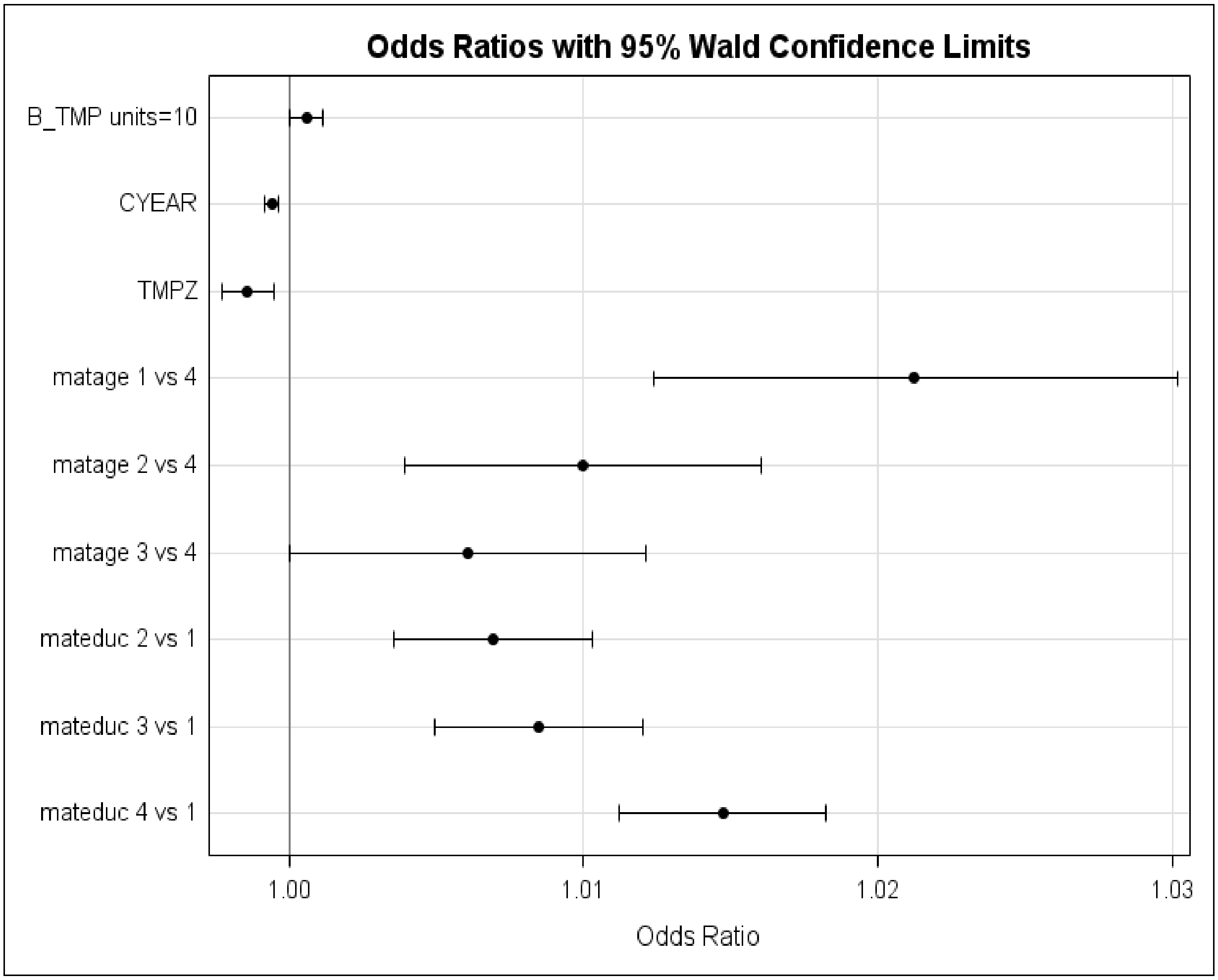


Figure 71. Odds ratio plots for fitted sex ratio and climate change model, 1989–2001 non-Hispanic white births, US large counties. Gestation and Plurality Odds Ratio values are omitted for scale. Code values are described in Table 20.

The model also fits better if the variable for number of cooling days in the month before conception (BCDD) is substituted for B_TMP. As discussed in the previous chapter, heating and cooling days are a proxy for temperature and may better reflect the nonlinear relationship of temperature to sex ratio than does degrees Fahrenheit. For births in the high latitude zones, the ENSO index is also a significant positive explanatory variable. This relationship suggests the possibility that climate variation cycles could be associated with SRB variation in the US. This model can also be satisfactorily fit excluding the decline year variable CYEAR for high latitude births using BCDD, TMZ, and the ENSO Index, and with BCDD and BTMPZ in low latitudes. Without the ENSO index, the BCDD variable is nearly significant (0.058) in the high latitude model without the CYEAR variable.

Further refinement or elucidation of these associations awaits a more sophisticated spatial-temporal method than used in this study. Latitudinal segmentation is an imperfect expression of the complex seasonal and geographic variation of the US sex ratio, while the geographic smoothing and weighted regression methods employed in the previous chapter do not accommodate well the seasonal time series analysis required to understand the relationship of climate and conception at the level of an individual birth.

Nonetheless, these logistic regression models all identify a significant association between the likelihood of conceiving a male and of deviation from normal temperatures during or before the month of conception for non-Hispanic births 1989–2001. The pattern of this relationship is shown in Figure 72, which shows that higher than normal temperatures are associated with a reduced probability of male conception. At the same time, colder than normal temperatures are associated with an increased probability of male conception. As Figure 73 shows, deviations from normal temperatures have increased in both high and low latitude locations. Approximately 20.1 percent of conceptions during the study period have occurred when the temperature is one or more standard deviations (SD) above normal during the month of conception, versus 13.8 percent occurring when temperatures are one or more SD below the 1971–2000 normal. Similarly, 19.72 percent conceptions have occurred when the temperature in the month before conception was one or more SD above normal, versus 13.9 percent one or more SD below normal.

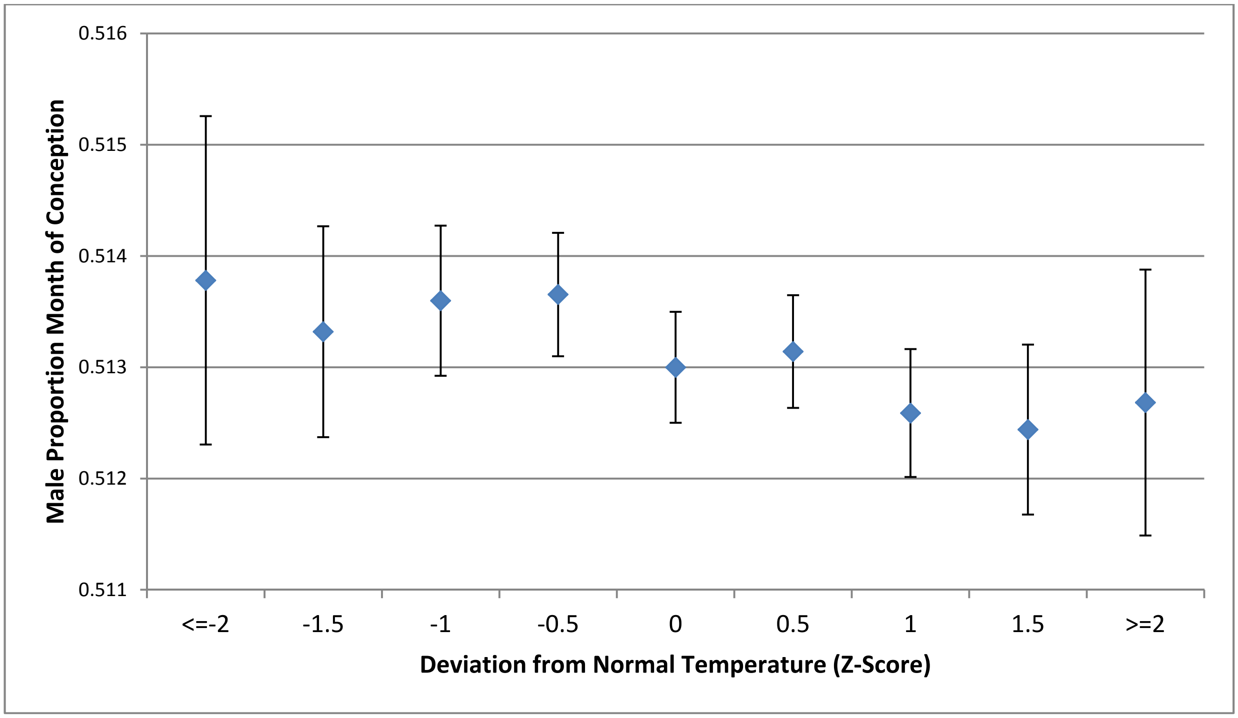
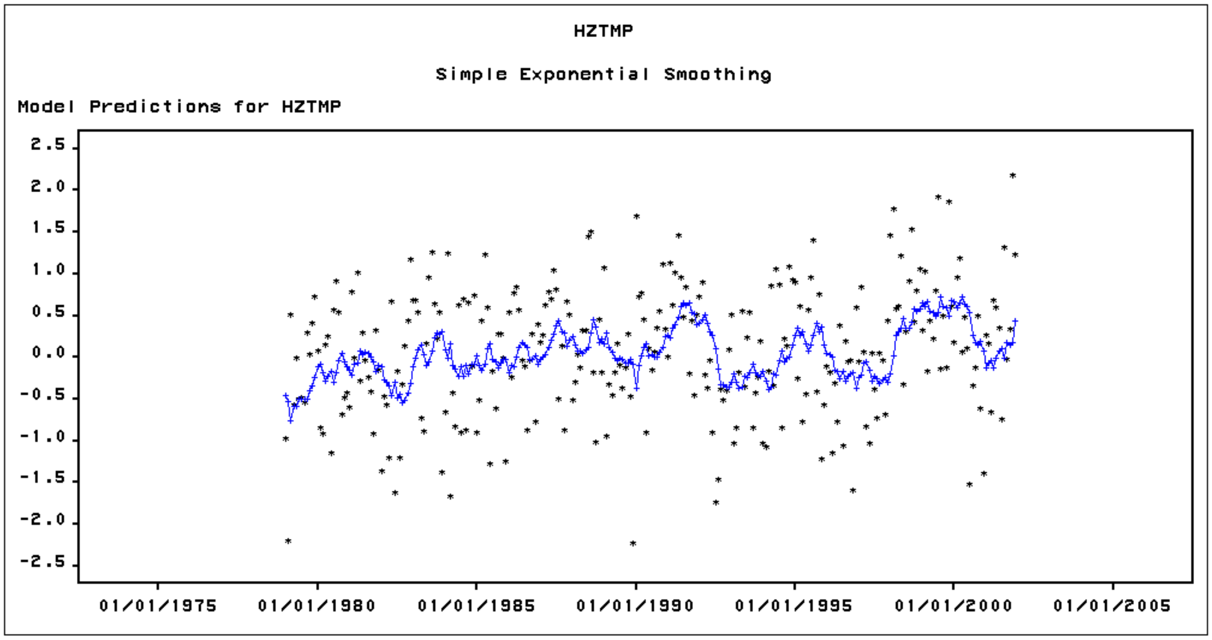


Figure 72. Estimated sex ratio at conception by z-score deviation of temperature during month of conception from 1971–2000 normals, non-Hispanic white births in US large counties 1989–2001. Categories are defined by rounding to near 0.5; vertical bars display confidence intervals.



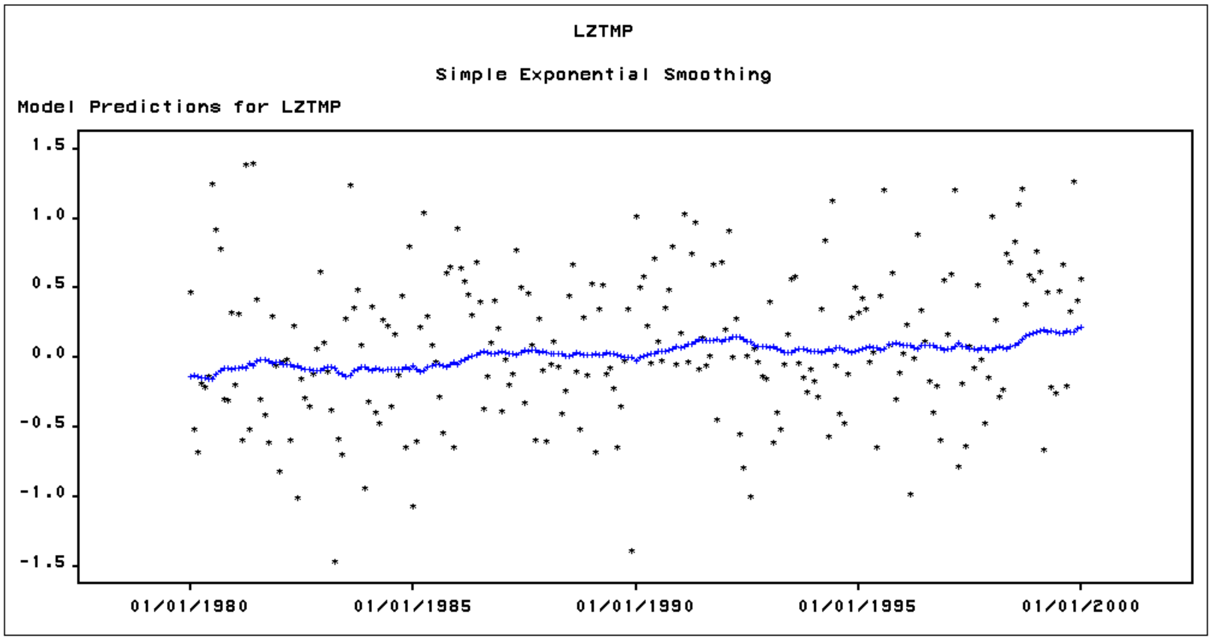


Figure 73. Time series models for deviations of monthly temperatures from 1971–2000 monthly normals expressed as z-scores for high latitude (HZTMP) and low latitude LZTMP) climate divisions associated with 403 US largest counties 1979–2001.

Given that higher than normal temperatures are associated with a decreased probability of male births, the skew toward higher temperatures due to climate change in the US warrants further investigation into climate related associations of SRB variation which may partially explain the recent decline in the US sex ratio at birth. However, this speculation is unsatisfying without an understanding of how deviation in temperature might cause a bias in the conception of males or females. In the final chapter I summarize the major findings of this study and relate them to hypothesized adaptive and proximate physiological mechanisms that might underlie this response.

Chapter 6: Summary and Conclusions

This study is a compilation of several separate spatial and temporal analyses that provide evidence of an association between climate and SRB that can be modeled along with previously documented individual biological factors. The key methodological finding of this study towards that end is that variation of sex ratio at birth is best studied in association with and as a function of birth rate. SRB is merely an expression of the different birth rates of males and females. Studies of the seasonality of SRB most often either omit discussion of birth rates or fail to find any significant interaction between the two. The seasonality of SRB is barely recognizable as more than white noise unless it is considered as a variation on the bass line of fertility. The observations of Lyster (1971) and Jongbloet et al. (1996) provide key insights into this relationship and serve as the basis for an argument that the decline in the sex ratio at birth is associated in part to increases in ambient temperatures during the study period. The findings of this study and my interpretations that support that argument are summarized in this chapter.

The Geography of US Fertility During the Study Period

To better understand the decline of the US sex ratio, I compared it to a number of measures of the seasonal fertility in the US. I did not research the seasonality and geographic variation in US fertility to the same degree as I did for SRB, but my investigation confirmed in broad strokes earlier work such as that of Lam and Miron (1996) and Seiver (1985, 1989). A seasonal exponential smoothing model of monthly estimated conception rates for non-Hispanic white births for 1979–2001 has an R^2 of 0.929. This model has a circannual wave that is remarkably constant over time. For non-Hispanic white births, this annual structure is anchored by trough in spring and peak of conceptions in the fall and early winter, resulting in a peak of late summer deliveries. A minor peak of conceptions occurs in June. This calendar agrees with that described by previous workers who found that most US births occur in summer and early autumn and the fewest in spring.

The seasonal patterns of US non-Hispanic white births also vary geographically. In considering geographic variation, I constructed spatial empirical Bayes smoothing (SEBS) maps to visualize seasonal differences and constructed two broad geographic latitudinal zones for statistical analysis. Births occur in climate division zones whose centroid latitude is 40 degrees or above are high latitude births; those below are low latitude births. After the minor June peak of conceptions, fertility drops during the summer in lower latitudes and peaks in October, November and December. In northern latitudes, there is a small drop after the June minor peak but than a recovery in ascent that continues through December. The trough of March births is lower in high latitudes than it is in low latitudes compared to the rest of the circannual pattern. The association of latitude and birth rate can also be detected in the movement of the mean latitude of births by season — northward during summer and fall and southward during winter and spring.

Geographic distribution of seasonal fertility can also be seen in the difference in monthly birth rates among non-Hispanic whites, non-Hispanic blacks, and Hispanic whites. The monthly variation in birth rate for non-Hispanic blacks and White Hispanic is highly correlated ($r_{pearson}$=0.85, $p<0.0001$), more so than are non-Hispanic whites and non-Hispanic blacks ($r_{pearson}$=0.439, $p<0.0001$) or non-Hispanic whites and Hispanic whites ($r_{pearson}$=0.655, $p<0.0001$). The high correlation between non-Hispanic blacks and Hispanic whites is probably due to their relatively higher geographic concentration in southern latitudes. Seiver (1989) suggests that at least part of the disparity of among the fertility rate in white and non-white is due to socioeconomic factors, specifically access to air conditioning. Groups with less access to air conditioning would have reduced coital rates in the high temperatures summer and thus a greater trough in April–May births, an effect especially noticeable in southern states. This amplitude of this pattern appears to have moderated in recent years, based on the exponential smoothing model I created for non-Hispanic black births.

Geographic variation in the seasonality of US births strongly supports the theory that it is primarily the result of biological influences, although the minor peak in June and major peak in December suggest that wedding and holiday calendars are also important. The attenuation of amplitude due to air conditioning is another sociological effect that must be considered in any model of influences. There is no consensus in the literature about the physiological causes of seasonal variation in human fertility, although its constancy is the subject of much biodemographic investigation. Ester Rizzi and Dalla-Zuanna (2007) noted the conflicting results of many of these studies and the complex matrix of hypothesized effects that can be built to describe the proximate mechanisms of seasonal variation. Sperm count, sperm motility, proportion of normally formed sperm, and testosterone levels have all been shown to vary seasonally, but not in consistent ways. Similarly, follicular length, egg quality, implantation success and other seasonal variations in female reproductive ecology have been shown to vary seasonally and in a different relationship to temperature, moisture, and daylength at different times of the year and in different ways than they affect male reproductive characteristics. Underlying the uncertainty of an equation with these separate and complex seasonally varying male and female influences is very little information about coital frequency, a highly varying individual factor that may also have seasonal components.

As such it is impossible to say what specific biological mechanisms underlie the seasonal variation of fertility, but this study confirms that its variation is strongly associated with light and temperature and varies by latitude. The number of daylight hours, or daylength, may be the underlying mediator of the seasonal conception rhythm, supplying an unvarying seasonal cue that varies by latitude. The later conception peak of southern latitudes could be related to the relatively later onset of longer days and reduced amplitude of the annual peak and trough of photoperiod length. A minor peak in the June conception rate could also be related to the summer solstice, perhaps a relict photoperiod cue of optimality that is mitigated by excessively high US summer temperatures. After June, there is a significant drop in conceptions in low latitudes compared to high latitudes.

However, it appears that a greater proportion of geographic variation in US fertility is associated with temperature variations than of variation in daylength. Temperature, which is highly correlated to daylength in the US when lagged by one month, is also strongly correlated to variation of US fertility when it is lagged by one or more months. In high latitudes, monthly temperature one and two months prior to conception is strongly positively correlated to month conception rates ($r_{pearson}$ =0.72, $p<0.0001$; $r_{pearson}$ 0.82, $p<0.0001$, respectively). Daylength is also strongly correlated, but apparently lagged by one month, with the strongest correlations occurring two and three months prior to conception ($r_{pearson}$ =0.75, $p<0.0001$; $r_{pearson}$=0.88, $p<0.0001$, respectively). In low latitudes, there is an additional month of lag, with the strongest correlations in temperature occurring two and three months prior to conception ($r_{pearson}$ =0.61, p<0.0001, $r_{pearson}$ 0.74, p<0.0001, respectively); daylength is the month before conception is not significantly correlated to conception and the correlations in daylength values lagged by two and three months are less than that of temperature.

These correlations show that the association of temperature and fertility is significant but nonlinear and varies according geographic location. The association of temperature and fertility is readily seen on SEBS maps of climate division birth rates by season. These reveal a spatially varying *high temperature suppression effect* that reduces conceptions. Lam and Miron 1994, 1996, and Seiver 1985, 1989 and others have documented this effect for US births. The suppression effect on summer conceptions in low US latitudes is not as severe in high US latitudes, where the optimal season for conception begins earlier. SEBS maps in this study show that preferential seasons for fertility can vary within the same broad latitude zone and provide a clearer picture of seasonal and geographic variation than do regression or correlation analysis. In the southeast US, for example, spring conceptions are preferred to summer conceptions compared to the rates in the Midwest and Northwest, while fall appears to be the preferred conception season in the southwest US.

Lam and Miron (1996) concluded in a cross-national study of fertility that human births have a natural tendency to peak in the spring, as they do in many species, but that in warm climates hot summer temperatures suppress conception, resulting in a spring trough of births. If so, this explains why the relatively mild summers of Europe allow a peak of spring births while the hot summers of the southern US produce a trough of births in April and May. In northern states the spring trough is lower or nonexistent. They did not find that cold temperature *per se* was associated with fewer conceptions, but rather that above normal temperatures were correlated to decreases in fertility. In most states, an increase of 10 degrees F mean temperature at about 75 degrees F would decrease fertility by 4 to 6 percent, while an increase of 10 degrees F at 90 degrees F would reduce fertility 6 to 10 percent in some states. The geographic and seasonal variation I found in this study supports the theory that very warm temperatures suppress conceptions. Both exponential smoothing model and spectral analysis of fertility expressed as adjusted monthly birth rates for annual terms show a sine wave pattern with a consistent trough in the same month of the year in both high and low latitudes (March). Since this is closer in time to the annual low in temperature than it is with daylight, which occurs in December, temperature seems the most proximate explanation for the timing of the trough. The timing, phase, and amplitude of annual conception rates, however, differ between high and low latitudes and are more dissimilar in the latter part of the study period than they were in the initial portion. Given the leveling effect of air conditioning, more similar patterns would be expected.

The Geography of US Sex Ratio at Birth During the Study Period

The seasonality of the US sex ratio found by Slatis (1953), Lyster (1971) and others is also detectable for births during the 1979–2001 study period, although this seasonality is harder to detect and has a more complex temporal and spatial pattern than does fertility. During the study period, seasonality of the overall US sex ratio at birth lagged to conception month can be detected in a log seasonal exponential smoothing model and in non-Hispanic white births using a seasonal exponential smoothing model. Compared to birth rates, the R^2 of these models is low (0.01). Further, seasonality cannot be detected in time series analysis of non-Hispanic black births or Hispanic white births. Time series analysis shows that seasonality in conception month sex ratio is more easily detectable in low latitude non-Hispanic births than those in high latitudes.

When aggregated over the study period, seasonality of sex ratio is moderately but significantly correlated with birth ratio in low latitudes ($r_{pearson}$ =0.19, p<0.0001), but not in high latitudes ($r_{pearson}$=0.05, p=0.41). While the sex ratio at conception somewhat follows the rise and fall of fertility through the season, the peak of male conceptions occurs *before* the highest season of conceptions in the fall in both high and low latitudes (Figure 74). This lag between sex ratio peak and fertility peak was first noted in US births by Lyster (1971), who found a similar lag in SRB and birth rate to mothers in Wales, although the timing of the peaks was different. Jongbloet et al. (1996) describe a “double hump” relationship between SRB and fertility, with a peak of fertility separating two peaks of SRB, a pattern he claims to have found in historical statistics from the Netherlands, Germany, the US, Australia and the Southern hemisphere. He also cites Wolder (1927, 1935), who found a similar pattern in domestic animals and humans.

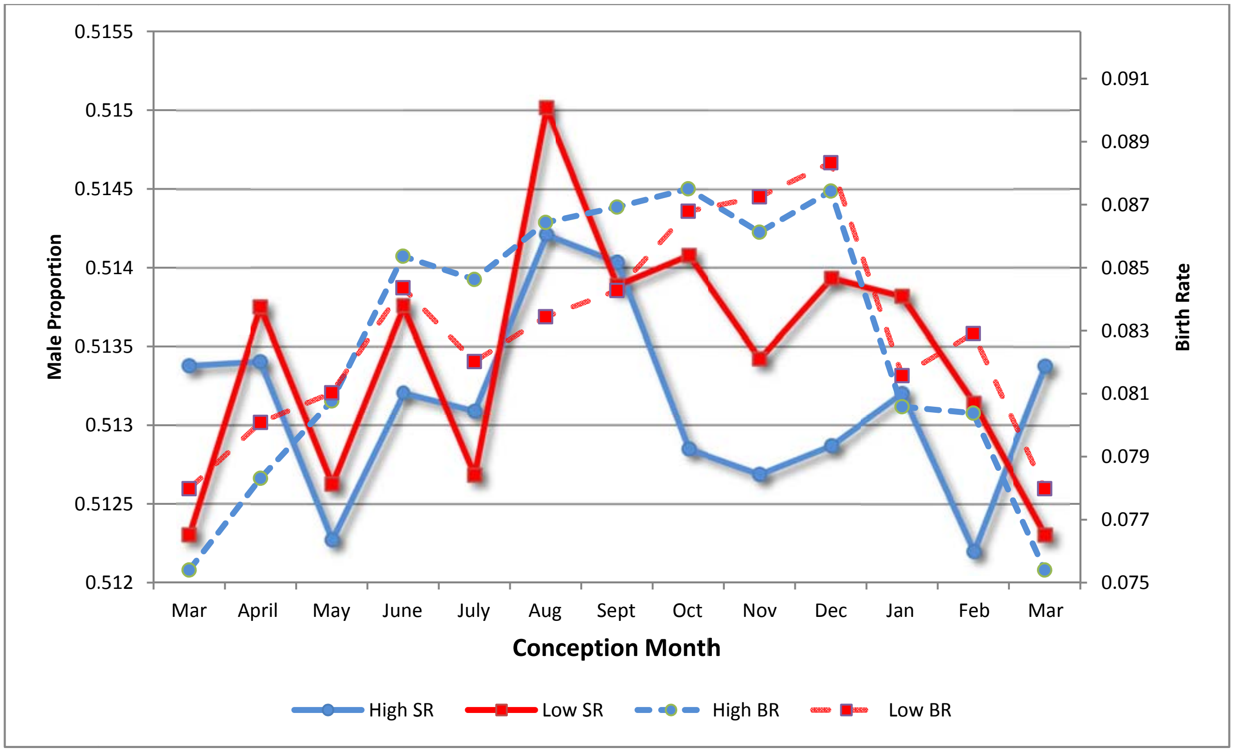


Figure 74. Birth monthly birth rate and sex ratio at birth lagged to conception month by latitude zone, non-Hispanic white births, US large counties, 1979–2001.

I found a similar double-humped pattern in the earliest years of the 1979–1988 study period. More consistently, the lag in sex ratio lagged to conception compared to the seasonal peak of fertility described by Lyster (1971) is present in the seasonal comparisons I performed for both high and low latitude births.

The proximate mechanism that Jongbloet et al. (1996) describe for the double hump pattern is complex but may provide a physiological basis for the changes that have occurred during the study period. Some research supports the hypothesis that equal numbers of males and females are conceived at the time of ovulation in midpoint of a conception cycle, while males are conceived at both the beginning and end of these cycles (e.g., James 1996). This is the optimal window of the ovulatory cycle. Some research into seasonal mating has found that the SRB is most equal at the peak of the mating season, while SRB is higher at the beginning and end of the mating cycle (Wolda 1935, Lambin 1994), an annual replication of the pattern of the monthly cycle. Jongbloet et al. (1996) claim that seasonal SRB patterns are the result of seasonal variation in non-optimal maturation of the egg ("seasonal pre-ovulatory overripeness ovopathy"). Among other effects, this condition allows the smaller Y-bearing sperm an advantage in penetrating cervical mucus that has not fully liquefied in synchrony with the fully matured egg, resulting in an excess of male births. Conversely, as the egg ages, preferential fertilization by Y-bearing sperm will result in an excess of poorly implemented or developed males, resulting in a decrease in sex ratio.

In reviewing the argument of Cagnacci et al. (2003) that warm temperatures in the month prior to conception produce more males, Jongbloet (2003) counters:

> *....at the peaks of the seasonally bound ovulatory rate there is a tendency to equity in the sex distribution (and to optimal conceptuses); at the breakthrough and breakdown, more males than females are conceived (and less optimal conceptuses); and, in the most constrained conditions, the SR becomes inverted due to excessive loss of male-biased (pathological) fetuses.*

This mechanism explains why sex ratio might decline in the presence of warm temperatures (optimality means a nearly even sex ratio) and increase in the presence of cold temperature extremes (male conceptions prior to the optimal season). While this explanation provides a proximate mechanism for seasonal SRB variation, I suggest that earlier conception of males also has an adaptive value for the most reproductively fit mothers. The consistent appearance of a peak of male conception before the optimal fertility season may reflect a facultative biological adjustment to allow the larger and developmentally more fragile male to gain extra advantage by being born earlier in the nurturing season to allow the greatest window of resource availability. This is consistent with the facultative adjustment hypothesis of Trivers Willard (1973), who predict that mothers in good condition will produce more males and that more males will be born when environmental conditions are most favorable. The season when children are born has been shown to explain the variability of a number of health characteristics, including future reproductive success. In a study of Austrian university men aged over 45, for example, those born in the spring had a higher number of offspring than those born in the autumn (Huber et al. 2003).

If the theory of Jongbloet et al. (1996) is correct, it follows that the relationship of SRB to temperature will be less apparent than it is for fertility. There is a significant correlation of temperature in the month before conception and sex ratio at conception in high latitudes (($r_{pearson}$ =0.14, p=0.018) and low latitudes ($r_{pearson}$ =0.13, p=0.029), as well as for daylength in the previous month in high latitudes ($r_{pearson}$ =0.125, p=0.037). The association is also significant for temperature two and three months prior to conception in low latitudes but not high latitudes.

This study, however, finds that in US non-Hispanic white births there is a significant positive relationship between temperature in the month before conception and the probability of conceiving a male, similar to the finding of Cagnacci et al. (2003) and Lerchl (1999). This association has not been found previously in US births, as far as I know, but it is confirmed by logistic regression models of individual births for the study period that control for individual factors. For all non-Hispanic white births conceived from 1989–2001, the temperature in the month before conception variable is significantly positively associated with increased sex ratio even when it is a single independent variable in the a model (p=0.007). It is a significant exploratory variable in all logistic regression models I built for the 1979–1988 period for all births and non-white Hispanic births, and for all non-Hispanic white births conceived in large population US counties 1979–2001 and for 1989–2001. Among all climate variables evaluated, the only variable that exceeds it in quantitative explanatory power is the number of cooling days in the month before conception (B_CDD), which provides a clearer contrast between summer temperatures (higher monthly averages of cooling days) and winter temperatures (zero value monthly average cooling days). The number of daylight hours in the month before conception (BDAYL) is also significant in a univariate model, but less so (p=0.02) and does not survive in model fitting when both temperature and daylength variables are considered.

The relationship of temperature to sex ratio at birth is complicated by its geographic stationarity in the US. The overall SRB decreases with higher latitudes in the US, similar to the finding of Grech et al. (2000) in a study of European latitudinal gradients of SRB. When used as single explanatory variables for non-white Hispanic births for 1989–2001, each degree of latitude decreases the probability of a male conception by 0.00019 (p=0.047). The latitudinal orientation of spatial nonstationarity in non-Hispanic births can also be seen in a SEBS map of total SRB rates for all non-white Hispanic births for 1989–2001 (Figure 75).

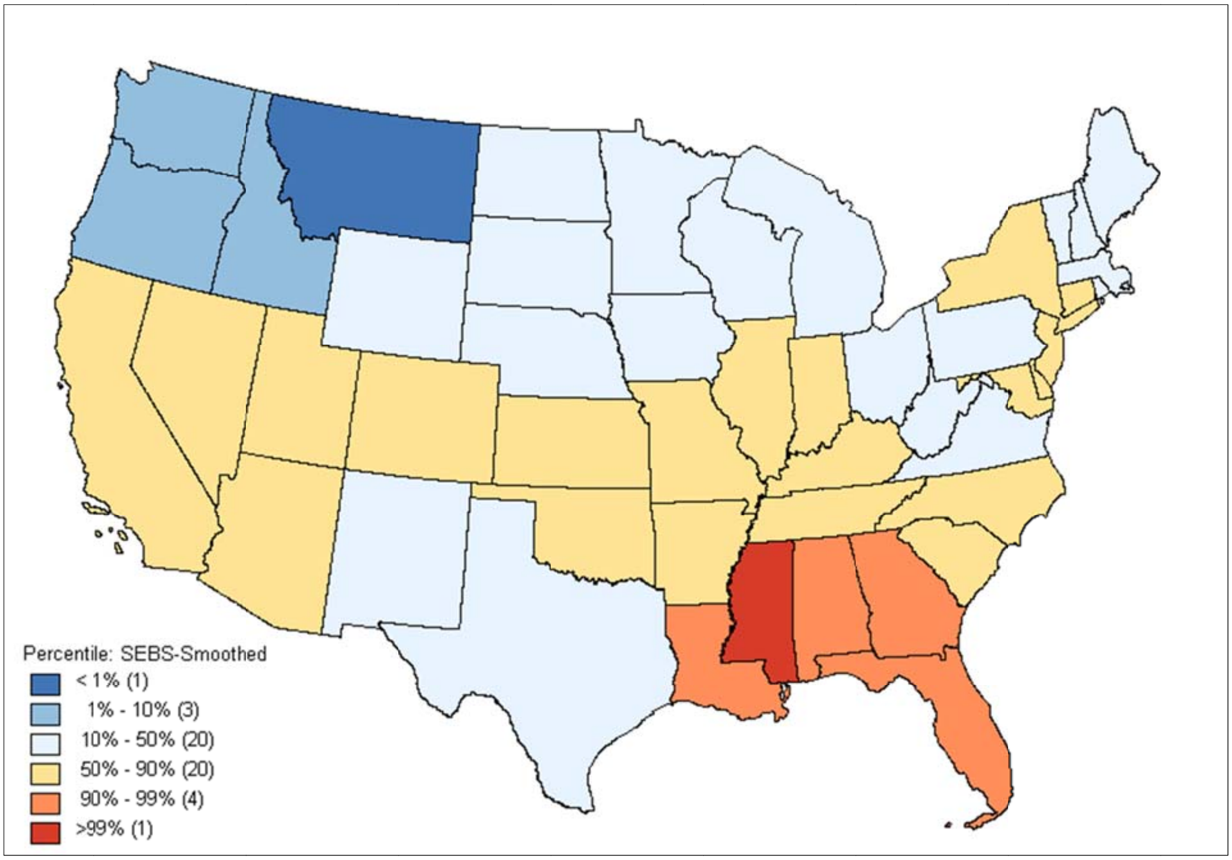
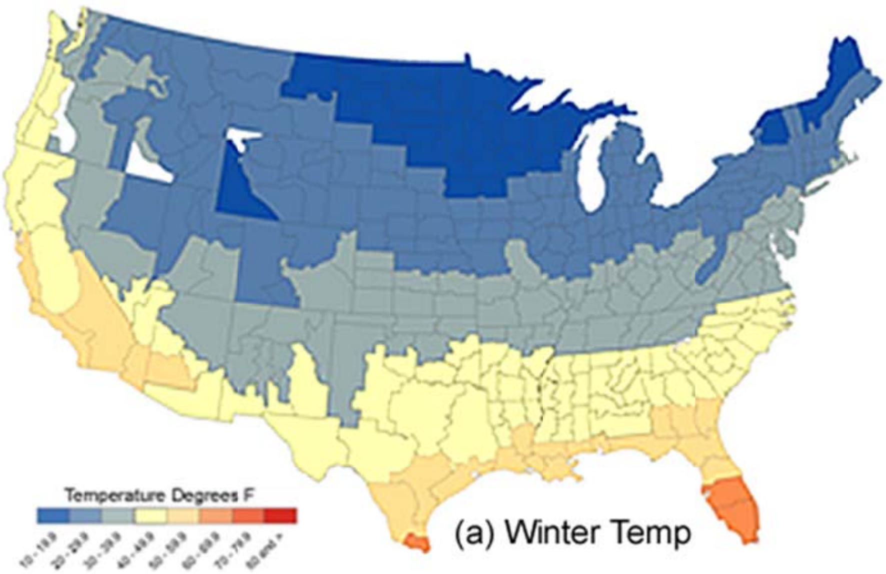


Figure 75. Percentage map from spatial empirical Bayes smoothing of all Map of rate of non-Hispanic white boys by total Hispanic white births by state, 1989–2001. Weighting created by threshold Euclidean distance (509000 m) using state centroids.

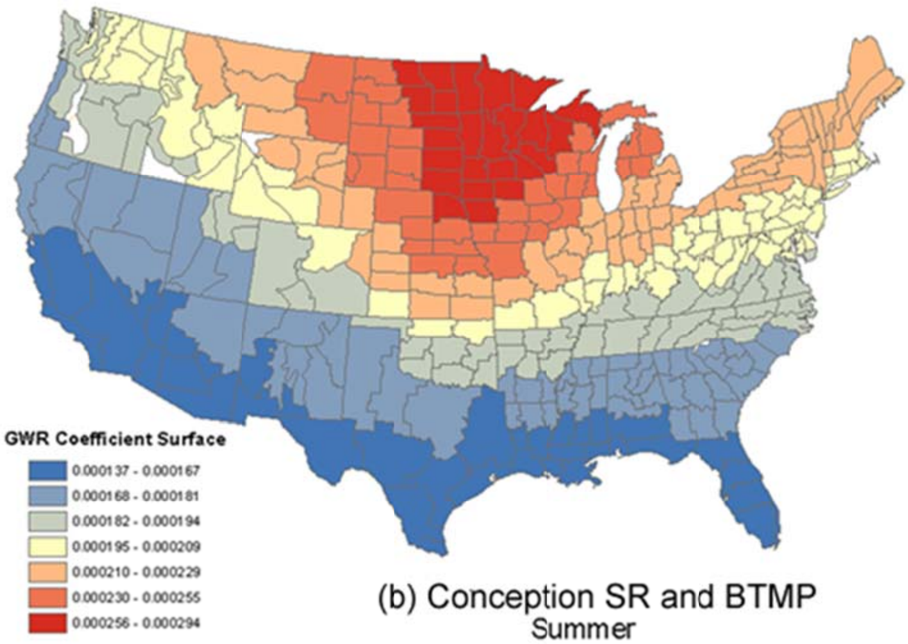
SRB varies within broad latitude zones as well as between them. When all climate divisions were examined for the period 1979–1988, sex ratio at birth is highest in the southeast US, excluding North Carolina, while the Rocky Mountain States and Upper Midwest have the lowest SRBs. Counter to arguments that lower latitudes produce more males are the low SRB rates of southwest Texas and the high SRB rates of northern Montana during this period. To understand how sex ratio at conception varies geographically in association with temperature, I constructed a local model of the response of the SR at conception for non-Hispanic white births 1978–1979 and seasonal temperature one month before conception (BTMP) using geographically weighted regression (GWR). Both GWR and OLS models were significant for summer and fall models of sex ratio at conception and BTMP. The coefficient surface of the summer GWR model shown in Figure 76 shows the highest association of temperature and SRB where winter temperatures are lowest. Even considering regional stationarity of SRB, the predilection to conceive males in the summer is relatively higher in colder regions of the US, where the variation between seasonal temperatures is highest and summer temperatures are significantly lower. Given the apparent suppression of fertility by hot temperatures, the seasonal variation in SRB may be a response to changes in the optimal season of fertility.

Decline of Sex Ratio at Birth Related to Climate Change

Establishing patterns of seasonal variation by latitude provides a baseline for examining the climate influence on the decline in sex ratio at birth in the US documented since 1970 (Mathews and Hamilton 2005). This study examined this decline in large US population counties from 1979–2001, and particularly since 1989 when the standard birth certificate included Hispanic origin reporting. Shifts in certain components of the demographics of US mothers require control to detect changes in SRB due to environmental factors. US Hispanic white populations have lower sex ratios than non-Hispanic white populations, possibly due to reduced medical access and lower socioeconomic circumstances. Increases in the composition of the Hispanic composition of the US population probably contributed to the overall decline of sex ratio during the study period, but a significant decline in non-Hispanic white births remains even after this is considered.



(a) Winter Temp



(b) Conception SR and BTMP
Summer

Figure 76. (a) Winter temperature by climate division, 1979–1988. (b) coefficient surface of geographically weight regression model of sex ratio lagged to summer conception season and aggregated seasonal temperature in month before conception, non-Hispanic white births, 1979–1988.

Similarly, changes in the age structure and partnership status of mothers have been considered by some researchers analyzing the decline of SRB. Significant changes in the relative percentages of pre-term, normal, and post-term births also required consideration, because sex ratio at birth is significantly different among these three gestation terms. Similarly, changes in the frequency of plural births could be associated with changes in overall SRB. While some of these factors, such as the increased composition of older mothers and single mothers, probably contributed to the decline in overall sex ratio, other factors, such as the increased percentage of normal and preterm births relative to post-term births, should result in an increase in sex ratio at birth rather than a decline, because normal and postterm births are more male-biased than postterm births. When considered in total, these biological and obstetric factors do not explain the decline in sex ratio at birth from 1979–2001.

In addition to the cultural changes reflected by these statistics, a significant increase in US seasonal temperatures occurred during the study period. I have shown that increased temperatures before the month of conception are significantly correlated to increases in fertility and SRB, but also that this association is nonlinear and varies in relation to the amplitude of other seasonal temperatures in the geographic region of occurrence. Changes in fertility patterns during the study period may be related to temperatures changes. At the beginning of the study period the amplitude of high and low latitude births is similar (Figure 77). Seiver (1985), Lam and Miron 1996, and others have documented a greater seasonal amplitude of fertility in southern states they speculate are due to greater summer temperatures, but in my study during the first eight years of the study period the average amplitude of the low latitudes is slightly lower than of high latitudes (94 percent, amplitude = ½ peak to peak value of adjusted monthly birth rate). During the final eight years of the study period the amplitude of low latitude fertility is only 67 percent of the high latitude amplitude. The timing of the peak of conceptions in high latitudes also moves to earlier in the season compared to low latitudes.

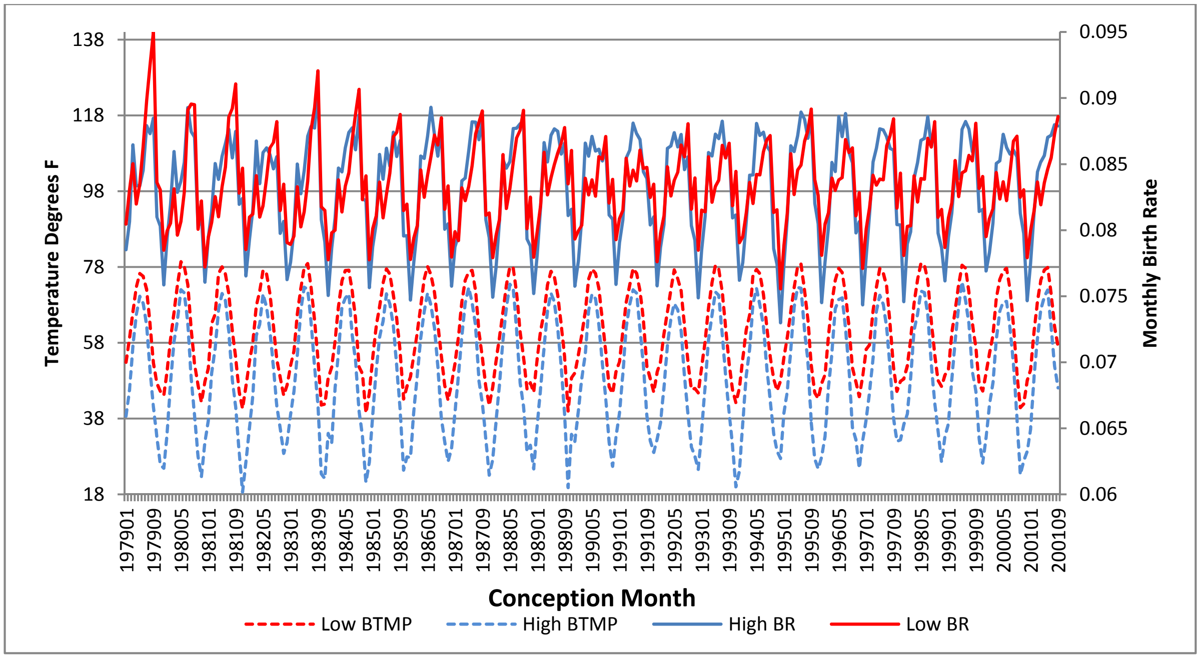


Figure 77. Monthly birth rate lagged to conception by latitude zone and month temperatures in the month before conception (BTMP), non-Hispanic white births, US large counties (1979–2001).

These are possibly partly due to demographic issues, such as the underreporting of Hispanic births in the early part of the study period and general migration of the US population towards Sunbelt states. It may also be a continuation of the trend documented by Seiver (1985) in which the trough of April–May births (from summer conceptions) decreased in those states with the greatest increase in air conditioning.

However, when the mean latitude of births from 1989 to 2001 are examined *within* latitude zones, the mean center of non-Hispanic white births in the higher latitudes of the US decreased by a rate of 0.0002 per month while the mean center of non-Hispanic white births in the lower latitudes increased by a rate of 0.0003 per month (Figure 78). There is also a disruption of the seasonal pattern towards the end of the period compared to the earlier period and to the pattern of southern births. These trends suggest that the summer fertility suppression effect is increasing in low latitudes, and has begun to become more of a significant factor in high latitudes, where it had formerly been a more favorable season for conception.

Changes in the seasonality of sex ratio at birth can also be seen during this period. When aggregated by season, seasonal sex ratio during the 1975–1985 period is similar in high and low latitudes, with a trough in spring in both latitudes zones and a summer peak in high latitudes and a fall peak in low latitudes. During the 1994–2001 period, the peak season for conception in high latitudes is spring, while it has shifted to summer in low latitudes. While the summer peak value in low latitudes is the same value as previously, the fall peak has diminished in both fertility and relative male proportion (Figure 79).

I showed that temperature in the month before conception (BTMP) is significantly positively correlated to SRB lagged to conception for 1978–1988 births when modeled with race, Hispanic origin, maternal age, socioeconomic status (i.e., maternal education), parity, plurality and nonspecified factors associated with gestation length. However, the model does not fit well for 1989–2001 births unless year of conception (CYEAR) is included to account for the decline in sex ratio during this period. To refit this model, an additional variable to account for SRB variation is required to account for extreme temperatures.

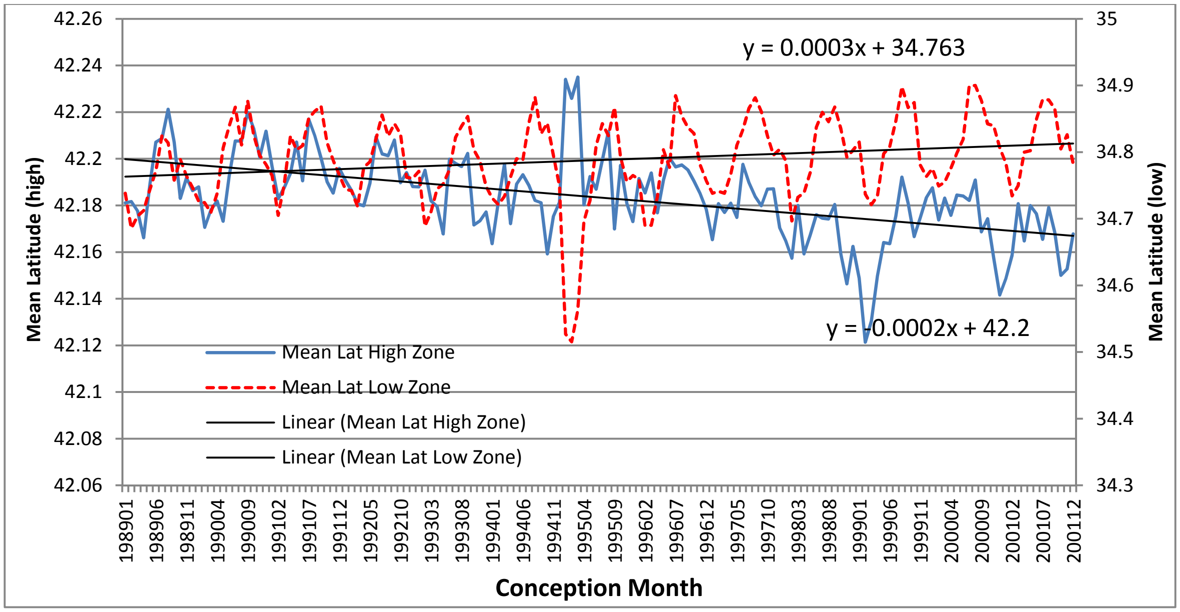
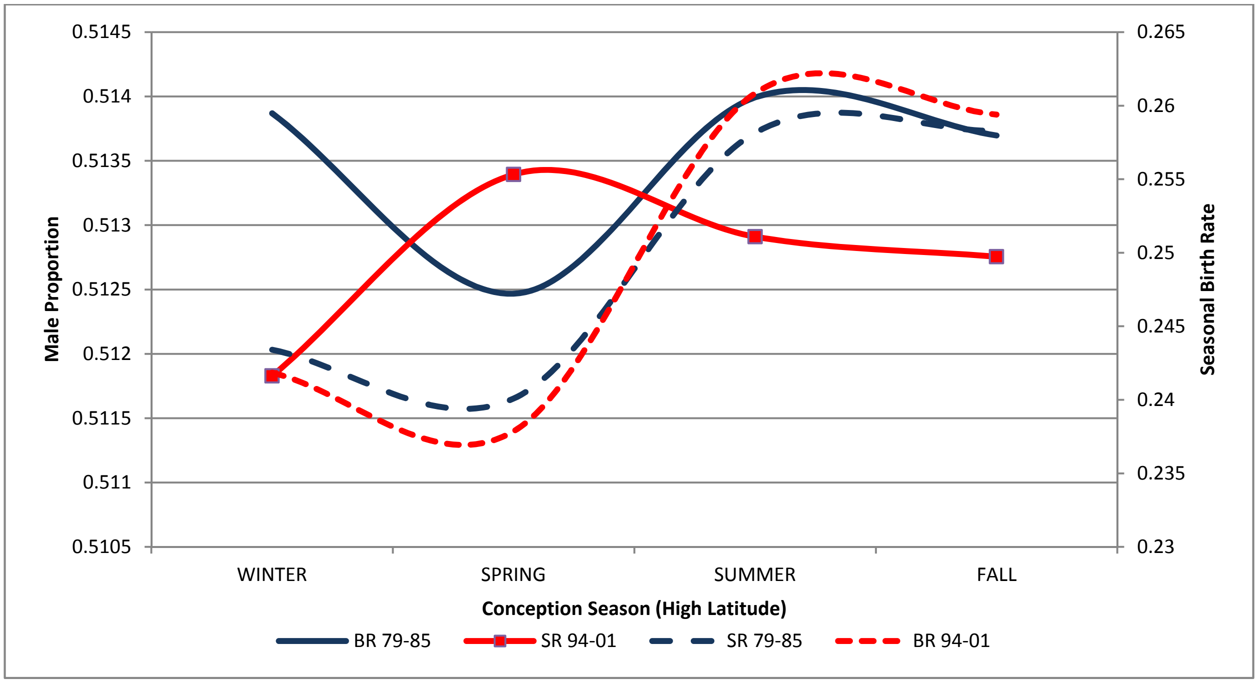


Figure 78. Mean latitude of births by latitude zone, non-Hispanic white births, US large counties, 1989–2001.



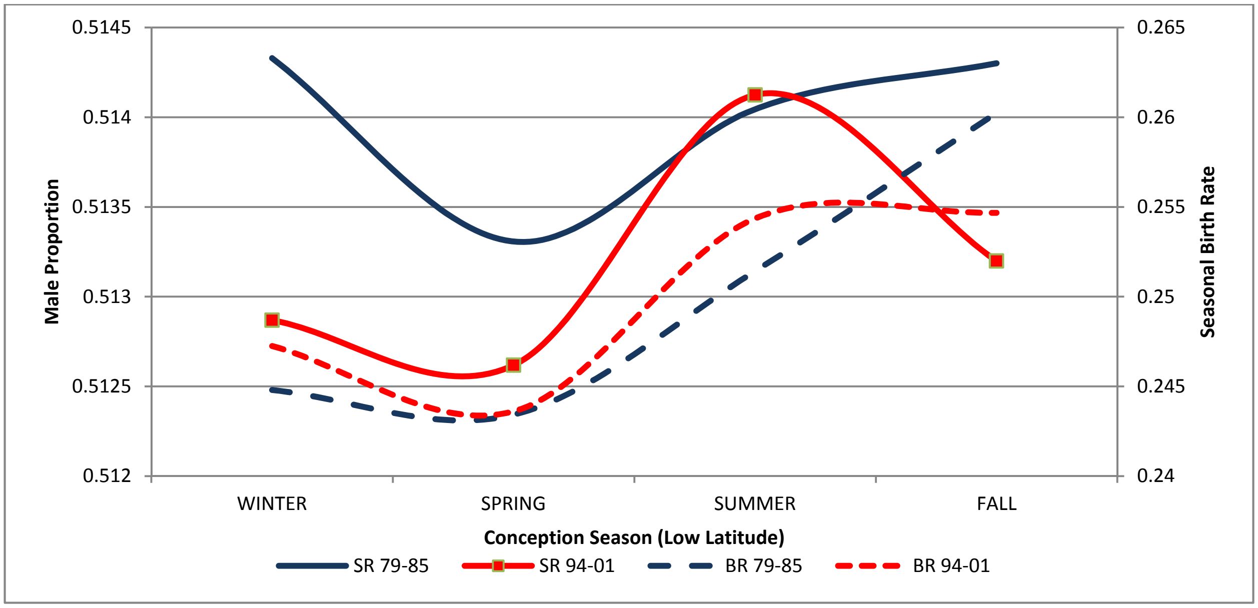


Figure 79. Conception sex ratio and birth rate by high latitude (top) and low latitude (bottom) for non-Hispanic white births 1979–1985 compared to 1994–2001, US large counties.

The model fits when deviation from normal temperatures (TMPZ) is added. The model fits best for high latitudes when this deviation is fit in the month of conception (TMPZ) and in low latitudes when deviation from the month before conception is used (BTMPZ). This normalized value is a standardized z-score for the temperature in month before or during conception calculated using mean monthly temperature values for the climate division during the 1971–2000 baseline period. The greater percentage of births occurring one or more standard deviations above normal (20.1) compared to those deviations towards colder temperatures (13.8) is an association that suggests a partial explanation for the decline in sex ratio during this period. Although ambient environment temperature is associated with the increase of a male birth and seasonal birth rates in general, excessively deviating temperatures — nonseasonal temperatures — can change this relationship, as was found by Lam and Miron (1996) in their study of the seasonality of fertility in relation to temperature.

One explanation for this response is that excessive temperatures disproportionately stress male fetuses. Catalano et al. (2008) found that extremely cold temperatures depressed SRB in a 19th century population of Danes, Finns, Norwegians, and Swedes. Although a similar association between extreme high temperatures and low SRB has not been found, the argument of Catalano and his colleagues may also be applied: natural selection will tend to cull male fetuses that would otherwise survive in more moderate temperature. High temperatures have a number of damaging physiological effects. Sperm in most mammals will not mature at normal body temperatures and must be created in an external scrotal sac where they can be generated at a few degrees lower than body temperature. In another study, Catalano and his coworkers (2006) found that exogenous stressors such as the events associated with September 11, 2001 attacks resulted in a “male flush” in the months immediately following the attacks. That is, the stress of these events did not result in a decrease in the sex ratio 8, 9, or 10 months following the attack, but did result in increase in sex ratio three months after the attack because all near term males were stressed into immediate delivery. The interaction of suppressed conception of males after extremely warm weather and excess fetal loss associated with these events may interact to result in an increase of male births nine months after these events but this cannot be detected with the approach used in this study, nor without consideration of fetal loss statistics. The hypothesis that male conception is suppressed during extremely hot temperatures is supported by the geographic preference of summer male conception in high latitudes compared to low latitudes that are presented in this study. However, as Jongbloet et al. (1996) suggest, constrained conditions cause excessive loss of male fetuses, resulting in an inversion of the sex ratio.

A second and possibly related explanation is that SRB declines are related to the shift in the timing of the male conception peak. The annual peak of SRB has shifted to earlier in the year in both high and low latitude zones as shown by the seasonal aggregations in Figure 79. In high latitude zones, the annual peak of SRB in the 1994–2001 period shifted to one month earlier; in low latitude zones, the annual peak of SRB is two months earlier. Figure 80 compares the monthly SRB values for the two periods for high and low latitude zones, with a 1 and 2 month lead period, respectively, also displayed. Following the arguments of Jongbloet et al. (1996), these shifts could have been caused by extensions in the optimal fertility season. In high latitudes the earlier onset of the summer conception peak shown in these figures would also cause a shift in SRB if the observed lagged relationship between SRB and fertility continues to operate as a reproductive strategy. In low latitudes, summer has replaced fall as the peak season of conception, also shifting the peak of SRB from fall to summer. If this is the case, the circannual arc of conception is out of phase with previously established rhythms. Proportionately more conceptions would occur during higher temperatures, when male fetuses may experience greater than normal stress.

The increased length of the optimal birth season due to higher temperatures may also be associated with changes in the sex ratio at birth. The earlier seasonal peak of fertility in high latitudes shown in this study is possibly a result of spring occurring earlier in the year, a phenomenon more pronounced in higher US latitudes than lower ones (Parmesan 2006).

Although Jongbloet et al. (1996) do not relate their seasonal preovulatory ovopathy hypothesis to the decline of the sex ratio at birth, the theory suggests two ways in which sex ratio might decline in the face of higher temperatures:

1. Increased male fetal loss in non-optimal seasons. An excess of males are conceived when conditions are not optimal due to the smaller size of the Y-bearing sperm. Extreme temperatures cause the loss of fetuses, resulting in a higher percentage of.

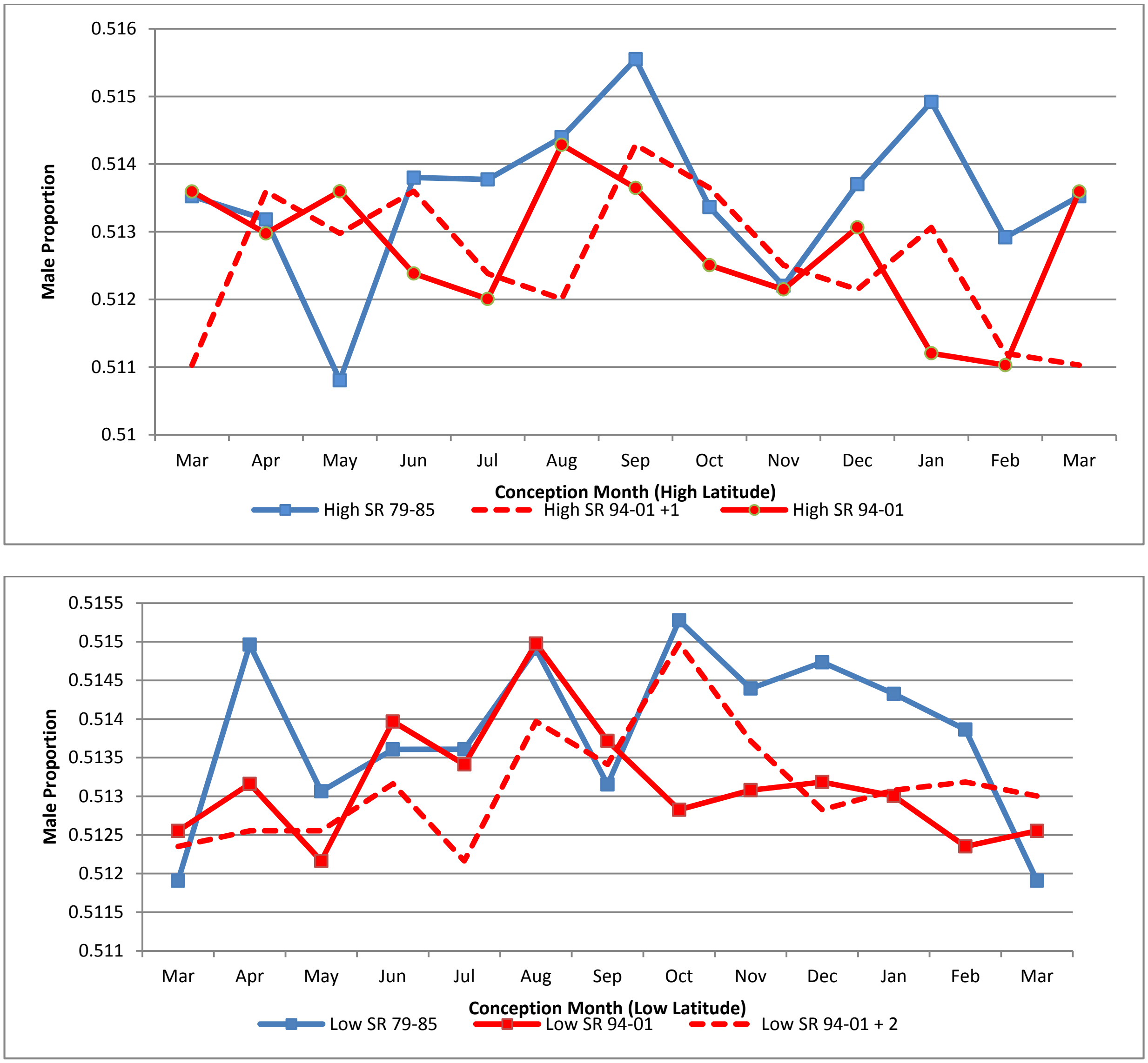


Figure 80. Monthly aggregation of sex ratio lagged to conception for 1979–1985 and 1994–2001 births, by latitude zone. 1994–2001 values are led by one month for high latitude births and by two months for low latitude births.

2. successful female births. I have shown that extremely high temperatures are associated with a reduced sex ratio at conception and suppressed conception. Longer optimal seasons. When cervical conditions are optimal, both Y-bearing and X-bearing sperm have equal success in reaching the oocyte. The net effect of this longer period of optimality would be also a reduction of sex ratio. Shorter winters and earlier onset of spring as a result of climate change in the US have extended the number of warm days in each year. The earlier seasonal peak of male births that has occurred over the study period may also be associated with the earlier onset of warm temperatures.

If supported by further research, changes in optimal season length and schedule of human conception would add *Homo sapiens* to the list of species that have undergone reproductive timing shifts documented by wildlife ecologists as a result of climate change. While industrial society humans are not under the immediate threat that affects many other species whose reproductive life cycles have been altered, change in fertility and SRB seasonality forebodes potentially significant human health impacts.

Suggestions for Future Research

The study of climate change impacts on human health have previously been limited to assessments of thermal stresses or to secondary effects such as trauma from extreme weather events and exposure to changes in the patterns of vector borne diseases. My hope is that the present study will contribute to biodemographic research in which human biology is not considered immune to the widespread and rapid changes in the natural world that are being documented in the face of climate change. The study of the geographic variation of SRB can contribute significantly to this biodemographic framework. While similar studies in other locations than the US would contribute this this research, I will describe here opportunities to mine further the wealth of SRB data from NCHS.

As long as this birth data exists, the prospect for future SRB research is assured, but the difficulty of obtaining geographically referenced birth data from the NCHS since 2003 has unfortunately obscured a critical term in the equation of sex ratio variation. My understanding is that the process of obtaining this data has been somewhat eased since the start of my study.

My recommendation is that data of most concern to health information confidentiality restrictions be removed from a geographically referenced database easily available to health researchers.

The work in this study examines the temporal and spatial SRB variation of live births. Study of NCHS linked birth/infant death data is necessary to understand better how recent climate change might affect the viability of a male or female conceived in different seasons and different locations. The relative occurrence of preterm, term, and postterm births has also changed significantly over the study period but there has been no study of the geography of this change.

Using a geographically complete database of NCHS data, further work can be done to extend the spatial analysis of the 1979–1988 climate division data to discover how the broad shifts in the timing of seasonal SRB from 1979–2002 documented in this study are reflected in regional geographic distribution of SRB. Further, the very clear seasonal patterns of seasonal fertility mapped by spatial smoothing for 1979–1988 are likely to have undergone change, given the shifts of monthly and seasonal mean latitudes of births that are graphed here. This spatial analysis may provide further insight in the possibility of phenological change in the seasonal rate and sex ratio of US births.

A more complete geographic and temporal analysis of the birth rate and SRB variation of US population groups other than non-Hispanic whites is also required to describe the relationship between climate and SRB. The variation in US population groups with Hispanic origin is complicated both by the uneven distribution of this population and the underreporting of Hispanic origin by some states until after 1989, as well as by the different structure of maternal age, birth order, and other birth demographics that could affect SRB. However, the monthly birth rate to black mothers and those of Hispanic origin has been shown to have a stable seasonal pattern and an understanding of its spatial and temporal relationship to SRB is necessary to expand understanding of how location can affect SRB variation in the US.

Although I have shown that temperature in the month before conception is significantly positively correlated to the likelihood of a male birth, this relationship varies geographically and seasonally. There are also interesting correlations with photoperiod and temperature at greater intervals than one month prior to conception. Since the timing of hormonal response implied by these correlations is not known, it would be interesting to examine the effect of two or three month intervals of these values using dynamic regression or other time series models that allowed more sophisticated examinations of the interrelationships of these values. Conversely, it would also be useful to study a population in which conception time and climate variables could be calibrated to within a few days, and the biological and socioeconomic status of both parents could be described in terms of other research related to SRB variation. Changes in the likelihood of male conception in this well described population during or after extreme temperature events would also provide insights about the nature of human response to a changing climate.

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Appendices

Appendix 1. Counties Reassigned Climate Division Codes

Counties in which the weighted block group population centroid fell outside the climate division polygon were reassigned to the climate division listed in the table below.

FIPS Code	Area Name	Reassigned Climate Division Code and Name	Centroid Division Code
06003	Alpine, CA	0403 NORTHEAST INTER. BASINS	0405
06017	El Dorado, CA	0402 SACRAMENTO DRNG.	0402
06065	Riverside, CA	0406 SOUTH COAST DRNG.	0407
06067	Sacramento, CA	0402 SACRAMENTO DRNG.	0405
06071	San Bernardino, CA	0406 SOUTH COAST DRNG.	0407
06095	Solano, CA	0402 SACRAMENTO DRNG.	0402
08017	Cheyenne, CO	0503 KANSAS DRAINAGE BASIN	0501
08053	Hinsdale, CO	0502 COLORADO DRAINAGE BASIN	0505
08119	Teller, CO	0504 PLATTE DRAINAGE BASIN	0501
09001	Fairfield, CT	0603 COASTAL	0602
09009	New Haven, CT	0603 COASTAL	0602
09011	New London, CT	0603 COASTAL	0602
12011	Broward, FL	0806 LOWER EAST COAST	0805
12025	Miami-Dade, FL	0806 LOWER EAST COAST	0805
12085	Martin, FL	0806 LOWER EAST COAST	0805
12086	Miami-Dade, FL	0806 LOWER EAST COAST	0805
12087	Monroe, FL	0807 KEYS	0805
12099	Palm Beach, FL	0806 LOWER EAST COAST	0805
16003	Adams, ID	1005 SOUTHWESTERN VALLEYS	1004
16013	Blaine, ID	1004 CENTRAL MOUNTAINS	1007
16031	Cassia, ID	1009 UPPER SNAKE RIVER PLAINS	1010
16035	Clearwater, ID	1002 NORTH CENTRAL PRAIRIES	1004
16037	Custer, ID	1008 NORTHEASTERN VALLEYS	1004
16039	Elmore, ID	1005 SOUTHWESTERN VALLEYS	1004
16043	Fremont, ID	1009 UPPER SNAKE RIVER PLAINS	1010
16049	Idaho, ID	1003 NORTH CENTRAL CANYONS	1004
16061	Lewis, ID	1002 NORTH CENTRAL PRAIRIES	1003
16065	Madison, ID	1009 UPPER SNAKE RIVER PLAINS	1010
16073	Owyhee, ID	1005 SOUTHWESTERN VALLEYS	1006
16083	Twin Falls, ID	1007 CENTRAL PLAINS	1006
23005	Cumberland, ME	1703 COASTAL	1702
23007	Franklin, ME	1702 SOUTHERN INTERIOR	1701
23009	Hancock, ME	1703 COASTAL	1702
23017	Oxford, ME	1702 SOUTHERN INTERIOR	1701
23021	Piscataquis, ME	1702 SOUTHERN INTERIOR	1701
23025	Somerset, ME	1702 SOUTHERN INTERIOR	1701
23027	Waldo, ME	1703 COASTAL	1702
23029	Washington, ME	1703 COASTAL	1702
25021	Norfolk, MA	1902 CENTRAL	1903
25025	Suffolk, MA	1902 CENTRAL	1903
32023	Nye, NV	2604 EXTREME SOUTHERN	2603
33009	Grafton, NH	2702 SOUTHERN	2701
35017	Grant, NM	2904 SOUTHWESTERN MOUNTAINS	2908
35035	Otero, NM	2908 SOUTHERN DESERT	2906

35043	Sandoval, NM	2902 NORTHERN MOUNTAINS	2902
36039	Greene, NY	3005 HUDSON VALLEY	3002
36043	Herkimer, NY	3006 MOHAWK VALLEY	3003
36093	Schenectady, NY	3005 HUDSON VALLEY	3002
36111	Ulster, NY	3005 HUDSON VALLEY	3002
36113	Warren, NY	3005 HUDSON VALLEY	3003
46015	Brule, SD	3906 CENTRAL	3909
46093	Meade, SD	3904 BLACK HILLS	3901
46103	Pennington, SD	3904 BLACK HILLS	3905
49001	Beaver, UT	4204 SOUTH CENTRAL	4201
49003	Box Elder, UT	4205 NORTHERN MOUNTAINS	4201
49005	Cache, UT	4203 NORTH CENTRAL	4205
49011	Davis, UT	4205 NORTHERN MOUNTAINS	4203
49021	Iron, UT	4204 SOUTH CENTRAL	4201
49023	Juab, UT	4204 SOUTH CENTRAL	4201
49045	Tooele, UT	4203 NORTH CENTRAL	4201
49049	Utah, UT	4205 NORTHERN MOUNTAINS	4203
49055	Wayne, UT	4204 SOUTH CENTRAL	4207
53007	Chelan, WA	4508 CENTRAL BASIN	4506
53009	Clallam, WA	4502 NE OLYMPIC SAN JUAN	4501
53017	Douglas, WA	4508 CENTRAL BASIN	4507
53031	Jefferson, WA	4502 NE OLYMPIC SAN JUAN	4501
53033	King, WA	4503 PUGET SOUND LOWLANDS	4504
53037	Kittitas, WA	4508 CENTRAL BASIN	4506
53039	Klickitat, WA	4506 EAST SLOPE CASCADES	4508
53041	Lewis, WA	4504 E OLYMPIC CASCADE FOOTHILLS	4504
53045	Mason, WA	4504 E OLYMPIC CASCADE FOOTHILLS	4501
53053	Pierce, WA	4503 PUGET SOUND LOWLANDS	4504
53057	Skagit, WA	4503 PUGET SOUND LOWLANDS	4504
53061	Snohomish, WA	4503 PUGET SOUND LOWLANDS	4504
53067	Thurston, WA	4504 E OLYMPIC CASCADE FOOTHILLS	4503
53069	Wahkiakum, WA	4501 WEST OLYMPIC COAST	4501
53073	Whatcom, WA	4503 PUGET SOUND LOWLANDS	4505
54023	Grant, WV	4606 NORTHEASTERN	4604
54025	Greenbrier, WV	4605 SOUTHERN	4604
54095	Tyler, WV	4601 NORTHWESTERN	4602
56023	Lincoln, WY	4802 SNAKE DRAINAGE	4803
56027	Niobrara, WY	4808 LOWER PLATTE	4807

Appendix 2. Largest US Counties 1979–2002

Counties geographically identified as county of resident in NCHS public use natality data through the study period are listed below.

FIPS Code	Area Name	NCHS Code	Climate Division Code and Name
01073	Jefferson, AL	01037	0102 APPALACHIAN MOUNTAIN
01015	Calhoun, AL	01008	0104 EASTERN VALLEY
01089	Madison, AL	01045	0101 NORTHERN VALLEY
01097	Mobile, AL	01049	0108 GULF
01101	Montgomery, AL	01051	0106 PRAIRIE
01125	Tuscaloosa, AL	01063	0103 UPPER PLAINS
04013	Maricopa, AZ	03007	0206 SOUTH CENTRAL
04019	Pima, AZ	03010	0207 SOUTHEAST
05119	Pulaski, AR	04060	0305 CENTRAL
05143	Washington, AR	04072	0301 NORTHWEST
06001	Alameda, CA	05001	0404 CENTRAL COAST DRNG.
06007	Butte, CA	05004	0402 SACRAMENTO DRNG.
06013	Contra Costa, CA	05007	0404 CENTRAL COAST DRNG.
06019	Fresno, CA	05010	0405 SAN JOAQUIN DRNG.
06023	Humboldt, CA	05012	0401 NORTH COAST DRAINAGE
06029	Kern, CA	05015	0405 SAN JOAQUIN DRNG.
06037	Los Angeles, CA	05019	0406 SOUTH COAST DRNG.
06041	Marin, CA	05021	0401 NORTH COAST DRAINAGE
06047	Merced, CA	05024	0405 SAN JOAQUIN DRNG.
06053	Monterey, CA	05027	0404 CENTRAL COAST DRNG.
06059	Orange, CA	05030	0406 SOUTH COAST DRNG.
06061	Placer, CA	05031	0402 SACRAMENTO DRNG.
06065	Riverside, CA	05033	0406 SOUTH COAST DRNG.
06067	Sacramento, CA	05034	0402 SACRAMENTO DRNG.
06071	San Bernardino, CA	05036	0406 SOUTH COAST DRNG.
06073	San Diego, CA	05037	0406 SOUTH COAST DRNG.
06075	San Francisco, CA	05038	0404 CENTRAL COAST DRNG.
06077	San Joaquin, CA	05039	0405 SAN JOAQUIN DRNG.
06079	San Luis Obispo, CA	05040	0404 CENTRAL COAST DRNG.
06081	San Mateo, CA	05041	0404 CENTRAL COAST DRNG.
06083	Santa Barbara, CA	05042	0406 SOUTH COAST DRNG.
06085	Santa Clara, CA	05043	0404 CENTRAL COAST DRNG.
06087	Santa Cruz, CA	05044	0404 CENTRAL COAST DRNG.
06089	Shasta, CA	05045	0402 SACRAMENTO DRNG.
06095	Solano, CA	05048	0402 SACRAMENTO DRNG.
06097	Sonoma, CA	05049	0401 NORTH COAST DRAINAGE
06099	Stanislaus, CA	05050	0405 SAN JOAQUIN DRNG.
06107	Tulare, CA	05054	0405 SAN JOAQUIN DRNG.
06111	Ventura, CA	05056	0406 SOUTH COAST DRNG.
06113	Yolo, CA	05057	0402 SACRAMENTO DRNG.
08001	Adams, CO	06001	0504 PLATTE DRAINAGE BASIN

FIPS Code	Area Name	NCHS Code	Climate Division Code and Name
08005	Arapahoe, CO	06003	0504 PLATTE DRAINAGE BASIN
08013	Boulder, CO	06007	0504 PLATTE DRAINAGE BASIN
08031	Denver, CO	06016	0504 PLATTE DRAINAGE BASIN
08041	El Paso, CO	06021	0501 ARKANSAS DRAINAGE
08059	Jefferson, CO	06030	0504 PLATTE DRAINAGE BASIN
08069	Larimer, CO	06035	0504 PLATTE DRAINAGE BASIN
08101	Pueblo, CO	06051	0501 ARKANSAS DRAINAGE
08123	Weld, CO	06062	0504 PLATTE DRAINAGE BASIN
09001	Fairfield, CT	07001	0603 COASTAL
09003	Hartford, CT	07002	0602 CENTRAL
09005	Litchfield, CT	07003	0601 NORTHWEST
09007	Middlesex, CT	07004	0602 CENTRAL
09009	New Haven, CT	07005	0603 COASTAL
09011	New London, CT	07006	0603 COASTAL
09013	Tolland, CT	07007	0602 CENTRAL
10003	New Castle, DE	08002	0701 NORTHERN
11001	District of Columbia	09001	1804 UPPER SOUTHERN
12001	Alachua, FL	10001	0802 NORTH
12009	Brevard, FL	10005	0804 SOUTH CENTRAL
12011	Broward, FL	10006	0806 LOWER EAST COAST
12025	Miami-Dade, FL	10013	0806 LOWER EAST COAST
12031	Duval, FL	10016	0802 NORTH
12033	Escambia, FL	10017	0801 NORTHWEST
12057	Hillsborough, FL	10029	0804 SOUTH CENTRAL
12069	Lake, FL	10035	0803 NORTH CENTRAL
12071	Lee, FL	10036	0805 EVERGLADES
12073	Leon, FL	10037	0801 NORTHWEST
12081	Manatee, FL	10041	0804 SOUTH CENTRAL
12083	Marion, FL	10042	0803 NORTH CENTRAL
12091	Okaloosa, FL	10046	0801 NORTHWEST
12095	Orange, FL	10048	0803 NORTH CENTRAL
12099	Palm Beach, FL	10050	0806 LOWER EAST COAST
12101	Pasco, FL	10051	0803 NORTH CENTRAL
12103	Pinellas, FL	10052	0804 SOUTH CENTRAL
12105	Polk, FL	10053	0804 SOUTH CENTRAL
12115	Sarasota, FL	10058	0804 SOUTH CENTRAL
12117	Seminole, FL	10059	0803 NORTH CENTRAL
12127	Volusia, FL	10064	0803 NORTH CENTRAL
13021	Bibb, GA	11011	0905 CENTRAL
13051	Chatham, GA	11025	0909 SOUTHEAST
13063	Clayton, GA	11031	0904 WEST CENTRAL
13067	Cobb, GA	11033	0902 NORTH CENTRAL
13089	DeKalb, GA	11044	0902 NORTH CENTRAL
13121	Fulton, GA	11060	0902 NORTH CENTRAL
13135	Gwinnett, GA	11067	0902 NORTH CENTRAL
13215	Muscogee, GA	11106	0904 WEST CENTRAL
13245	Richmond, GA	11121	0906 EAST CENTRAL

FIPS Code	Area Name	NCHS Code	Climate Division Code and Name
16001	Ada, ID	13001	1005 SOUTHWESTERN VALLEYS
17019	Champaign, IL	14010	1105 EAST
17031	Cook, IL	14016	1102 NORTHEAST
17043	DuPage, IL	14022	1102 NORTHEAST
17089	Kane, IL	14045	1102 NORTHEAST
17097	Lake, IL	14049	1102 NORTHEAST
17099	LaSalle, IL	14050	1102 NORTHEAST
17111	McHenry, IL	14056	1102 NORTHEAST
17113	McLean, IL	14057	1104 CENTRAL
17115	Macon, IL	14058	1104 CENTRAL
17119	Madison, IL	14060	1106 WEST SOUTHWEST
17143	Peoria, IL	14072	1104 CENTRAL
17161	Rock Island, IL	14081	1101 NORTHWEST
17163	St. Clair, IL	14082	1108 SOUTHWEST
17167	Sangamon, IL	14084	1106 WEST SOUTHWEST
17179	Tazewell, IL	14090	1104 CENTRAL
17197	Will, IL	14099	1102 NORTHEAST
17201	Winnebago, IL	14101	1101 NORTHWEST
18003	Allen, IN	15002	1203 NORTHEAST
18035	Delaware, IN	15018	1206 EAST CENTRAL
18039	Elkhart, IN	15020	1202 NORTH CENTRAL
18089	Lake, IN	15045	1201 NORTHWEST
18091	LaPorte, IN	15046	1201 NORTHWEST
18095	Madison, IN	15048	1205 CENTRAL
18097	Marion, IN	15049	1205 CENTRAL
18127	Porter, IN	15064	1201 NORTHWEST
18141	St. Joseph, IN	15071	1202 NORTH CENTRAL
18157	Tippecanoe, IN	15079	1204 WEST CENTRAL
18163	Vanderburgh, IN	15082	1207 SOUTHWEST
18167	Vigo, IN	15084	1204 WEST CENTRAL
19013	Black Hawk, IA	16007	1303 NORTHEAST
19113	Linn, IA	16057	1306 EAST CENTRAL
19153	Polk, IA	16077	1305 CENTRAL
19163	Scott, IA	16082	1306 EAST CENTRAL
20091	Johnson, KS	17046	1406 EAST CENTRAL
20173	Sedgwick, KS	17087	1408 SOUTH CENTRAL
20177	Shawnee, KS	17089	1406 EAST CENTRAL
20209	Wyandotte, KS	17105	1403 NORTHEAST
21067	Fayette, KY	18034	1503 BLUE GRASS
21111	Jefferson, KY	18056	1502 CENTRAL
21117	Kenton, KY	18059	1503 BLUE GRASS
22017	Caddo, LA	19009	1601 NORTHWEST
22019	Calcasieu, LA	19010	1607 SOUTHWEST
22033	East Baton Rouge, LA	19017	1606 EAST CENTRAL
22051	Jefferson, LA	19026	1609 SOUTHEAST
22055	Lafayette, LA	19028	1608 SOUTH CENTRAL
22071	Orleans, LA	19036	1609 SOUTHEAST

FIPS Code	Area Name	NCHS Code	Climate Division Code and Name
22073	Ouachita, LA	19037	1602 NORTH CENTRAL
22079	Rapides, LA	19040	1605 CENTRAL
22103	St. Tammany, LA	19052	1606 EAST CENTRAL
23005	Cumberland, ME	20003	1703 COASTAL
23011	Kennebec, ME	20006	1702 SOUTHERN INTERIOR
23019	Penobscot, ME	20010	1702 SOUTHERN INTERIOR
23031	York, ME	20016	1703 COASTAL
24003	Anne Arundel, MD	21002	1804 UPPER SOUTHERN
24005	Baltimore, MD	21003	1806 NORTHERN CENTRAL
24510	Baltimore city, MD	21004	1806 NORTHERN CENTRAL
24021	Frederick, MD	21011	1806 NORTHERN CENTRAL
24025	Harford, MD	21013	1806 NORTHERN CENTRAL
24027	Howard, MD	21014	1806 NORTHERN CENTRAL
24031	Montgomery, MD	21016	1806 NORTHERN CENTRAL
24033	Prince George's, MD	21017	1804 UPPER SOUTHERN
24043	Washington, MD	21022	1807 APPALACHIAN MOUNTAIN
25001	Barnstable, MA	22001	1903 COASTAL
25003	Berkshire, MA	22002	1901 WESTERN
25005	Bristol, MA	22003	1903 COASTAL
25009	Essex, MA	22005	1903 COASTAL
25013	Hampden, MA	22007	1902 CENTRAL
25015	Hampshire, MA	22008	1902 CENTRAL
25017	Middlesex, MA	22009	1902 CENTRAL
25021	Norfolk, MA	22011	1902 CENTRAL
25023	Plymouth, MA	22012	1903 COASTAL
25025	Suffolk, MA	22013	1902 CENTRAL
25027	Worcester, MA	22014	1902 CENTRAL
26017	Bay, MI	23009	2007 EAST CENTRAL LOWER
26021	Berrien, MI	23011	2008 SOUTHWEST LOWER
26025	Calhoun, MI	23013	2009 SOUTH CENTRAL LOWER
26049	Genesee, MI	23025	2010 SOUTHEAST LOWER
26065	Ingham, MI	23033	2009 SOUTH CENTRAL LOWER
26075	Jackson, MI	23038	2009 SOUTH CENTRAL LOWER
26077	Kalamazoo, MI	23039	2008 SOUTHWEST LOWER
26081	Kent, MI	23041	2008 SOUTHWEST LOWER
26093	Livingston, MI	23047	2010 SOUTHEAST LOWER
26099	Macomb, MI	23050	2010 SOUTHEAST LOWER
26115	Monroe, MI	23058	2010 SOUTHEAST LOWER
26121	Muskegon, MI	23061	2005 WEST CENTRAL LOWER
26125	Oakland, MI	23063	2010 SOUTHEAST LOWER
26139	Ottawa, MI	23070	2008 SOUTHWEST LOWER
26145	Saginaw, MI	23073	2007 EAST CENTRAL LOWER
26147	St. Clair, MI	23074	2010 SOUTHEAST LOWER
26161	Washtenaw, MI	23081	2010 SOUTHEAST LOWER
26163	Wayne, MI	23082	2010 SOUTHEAST LOWER
27003	Anoka, MN	24002	2106 EAST CENTRAL
27037	Dakota, MN	24019	2109 SOUTHEAST

FIPS Code	Area Name	NCHS Code	Climate Division Code and Name
27053	Hennepin, MN	24027	2106 EAST CENTRAL
27123	Ramsey, MN	24062	2106 EAST CENTRAL
27137	St. Louis, MN	24069	2103 NORTHEAST
27145	Stearns, MN	24073	2105 CENTRAL
27163	Washington, MN	24082	2106 EAST CENTRAL
28047	Harrison, MS	25024	2210 COASTAL
28049	Hinds, MS	25025	2207 SOUTHWEST
28059	Jackson, MS	25030	2210 COASTAL
29019	Boone, MO	26010	2302 NORTHEAST PRAIRIE
29047	Clay, MO	26024	2301 NORTHWEST PRAIRIE
29077	Greene, MO	26039	2304 WEST OZARKS
29095	Jackson, MO	26048	2301 NORTHWEST PRAIRIE
29099	Jefferson, MO	26050	2305 EAST OZARKS
29183	St. Charles, MO	26092	2302 NORTHEAST PRAIRIE
29189	St. Louis, MO	26096	2302 NORTHEAST PRAIRIE
29510	St. Louis city, MO	26097	2302 NORTHEAST PRAIRIE
30111	Yellowstone, MT	27056	2405 SOUTH CENTRAL
31055	Douglas, NE	28028	2506 EAST CENTRAL
31109	Lancaster, NE	28055	2506 EAST CENTRAL
32003	Clark, NV	29003	2604 EXTREME SOUTHERN
32031	Washoe, NV	29016	2601 NORTHWESTERN
33011	Hillsborough, NH	30006	2702 SOUTHERN
33015	Rockingham, NH	30008	2702 SOUTHERN
34001	Atlantic, NJ	31001	2802 SOUTHERN
34003	Bergen, NJ	31002	2801 NORTHERN
34005	Burlington, NJ	31003	2802 SOUTHERN
34007	Camden, NJ	31004	2802 SOUTHERN
34011	Cumberland, NJ	31006	2802 SOUTHERN
34013	Essex, NJ	31007	2801 NORTHERN
34015	Gloucester, NJ	31008	2802 SOUTHERN
34017	Hudson, NJ	31009	2801 NORTHERN
34021	Mercer, NJ	31011	2802 SOUTHERN
34023	Middlesex, NJ	31012	2802 SOUTHERN
34025	Monmouth, NJ	31013	2802 SOUTHERN
34027	Morris, NJ	31014	2801 NORTHERN
34029	Ocean, NJ	31015	2802 SOUTHERN
34031	Passaic, NJ	31016	2801 NORTHERN
34035	Somerset, NJ	31018	2801 NORTHERN
34037	Sussex, NJ	31019	2801 NORTHERN
34039	Union, NJ	31020	2801 NORTHERN
35001	Bernalillo, NM	32001	2905 CENTRAL VALLEY
36001	Albany, NY	33001	3005 HUDSON VALLEY
36007	Broome, NY	33003	3002 EASTERN PLATEAU
36013	Chautauqua, NY	33006	3009 GREAT LAKES
36027	Dutchess, NY	33013	3005 HUDSON VALLEY
36029	Erie, NY	33014	3009 GREAT LAKES
36055	Monroe, NY	33026	3009 GREAT LAKES

FIPS Code	Area Name	NCHS Code	Climate Division Code and Name
36059	Nassau, NY	33028	3004 COASTAL
36005	Bronx, NY	33029	3005 HUDSON VALLEY
36047	Kings, NY	33029	3004 COASTAL
36061	New York, NY	33029	3005 HUDSON VALLEY
36081	Queens, NY	33029	3004 COASTAL
36085	Richmond, NY	33029	3004 COASTAL
36063	Niagara, NY	33030	3009 GREAT LAKES
36065	Oneida, NY	33031	3006 MOHAWK VALLEY
36067	Onondaga, NY	33032	3010 CENTRAL LAKES
36071	Orange, NY	33034	3005 HUDSON VALLEY
36075	Oswego, NY	33036	3009 GREAT LAKES
36083	Rensselaer, NY	33039	3005 HUDSON VALLEY
36087	Rockland, NY	33040	3005 HUDSON VALLEY
36089	St. Lawrence, NY	33041	3008 ST. LAWRENCE VALLEY
36091	Saratoga, NY	33042	3005 HUDSON VALLEY
36093	Schenectady, NY	33043	3005 HUDSON VALLEY
36103	Suffolk, NY	33048	3004 COASTAL
36111	Ulster, NY	33052	3005 HUDSON VALLEY
36119	Westchester, NY	33056	3005 HUDSON VALLEY
37021	Buncombe, NC	34011	3101 SOUTHERN MOUNTAINS
37035	Catawba, NC	34018	3104 CENTRAL PIEDMONT
37051	Cumberland, NC	34026	3106 SOUTHERN COASTAL PLAIN
37057	Davidson, NC	34029	3104 CENTRAL PIEDMONT
37063	Durham, NC	34032	3103 NORTHERN PIEDMONT
37067	Forsyth, NC	34034	3103 NORTHERN PIEDMONT
37071	Gaston, NC	34036	3105 SOUTHERN PIEDMONT
37081	Guilford, NC	34041	3103 NORTHERN PIEDMONT
37119	Mecklenburg, NC	34060	3105 SOUTHERN PIEDMONT
37129	New Hanover, NC	34065	3106 SOUTHERN COASTAL PLAIN
37133	Onslow, NC	34067	3106 SOUTHERN COASTAL PLAIN
37155	Robeson, NC	34078	3106 SOUTHERN COASTAL PLAIN
37183	Wake, NC	34092	3104 CENTRAL PIEDMONT
39003	Allen, OH	36002	3301 NORTHWEST
39017	Butler, OH	36009	3308 SOUTHWEST
39023	Clark, OH	36012	3304 WEST CENTRAL
39025	Clermont, OH	36013	3308 SOUTHWEST
39029	Columbiana, OH	36015	3307 NORTHEAST HILLS
39035	Cuyahoga, OH	36018	3303 NORTHEAST
39049	Franklin, OH	36025	3305 CENTRAL
39057	Greene, OH	36029	3308 SOUTHWEST
39061	Hamilton, OH	36031	3308 SOUTHWEST
39085	Lake, OH	36043	3303 NORTHEAST
39089	Licking, OH	36045	3305 CENTRAL
39093	Lorain, OH	36047	3302 NORTH CENTRAL
39095	Lucas, OH	36048	3301 NORTHWEST
39099	Mahoning, OH	36050	3307 NORTHEAST HILLS
39103	Medina, OH	36052	3303 NORTHEAST

FIPS Code	Area Name	NCHS Code	Climate Division Code and Name
39113	Montgomery, OH	36057	3308 SOUTHWEST
39133	Portage, OH	36067	3303 NORTHEAST
39139	Richland, OH	36070	3306 EAST CENTRAL
39151	Stark, OH	36076	3307 NORTHEAST HILLS
39153	Summit, OH	36077	3303 NORTHEAST
39155	Trumbull, OH	36078	3303 NORTHEAST
39173	Wood, OH	36087	3301 NORTHWEST
40027	Cleveland, OK	37014	3405 CENTRAL
40031	Comanche, OK	37016	3407 SOUTHWEST
40109	Oklahoma, OK	37055	3405 CENTRAL
40143	Tulsa, OK	37072	3403 NORTHEAST
41005	Clackamas, OR	38003	3502 WILLAMETTE VALLEY
41029	Jackson, OR	38015	3503 SOUTHWESTERN VALLEYS
41039	Lane, OR	38020	3502 WILLAMETTE VALLEY
41047	Marion, OR	38024	3502 WILLAMETTE VALLEY
41051	Multnomah, OR	38026	3502 WILLAMETTE VALLEY
41067	Washington, OR	38034	3502 WILLAMETTE VALLEY
42003	Allegheny, PA	39002	3609 SOUTHWEST PLATEAU
42007	Beaver, PA	39004	3609 SOUTHWEST PLATEAU
42011	Berks, PA	39006	3603 SOUTHEASTERN PIEDMONT
42013	Blair, PA	39007	3608 SOUTH CENTRAL MOUNTAINS
42017	Bucks, PA	39009	3603 SOUTHEASTERN PIEDMONT
42019	Butler, PA	39010	3609 SOUTHWEST PLATEAU
42021	Cambria, PA	39011	3608 SOUTH CENTRAL MOUNTAINS
42027	Centre, PA	39014	3607 CENTRAL MOUNTAINS
42029	Chester, PA	39015	3603 SOUTHEASTERN PIEDMONT
42041	Cumberland, PA	39021	3604 LOWER SUSQUEHANNA
42043	Dauphin, PA	39022	3605 MIDDLE SUSQUEHANNA
42045	Delaware, PA	39023	3603 SOUTHEASTERN PIEDMONT
42049	Erie, PA	39025	3610 NORTHWEST PLATEAU
42051	Fayette, PA	39026	3609 SOUTHWEST PLATEAU
42055	Franklin, PA	39028	3604 LOWER SUSQUEHANNA
42069	Lackawanna, PA	39035	3601 POCONO MOUNTAINS
42071	Lancaster, PA	39036	3603 SOUTHEASTERN PIEDMONT
42075	Lebanon, PA	39038	3603 SOUTHEASTERN PIEDMONT
42077	Lehigh, PA	39039	3602 EAST CENTRAL MOUNTAINS
42079	Luzerne, PA	39040	3601 POCONO MOUNTAINS
42081	Lycoming, PA	39041	3605 MIDDLE SUSQUEHANNA
42085	Mercer, PA	39043	3610 NORTHWEST PLATEAU
42091	Montgomery, PA	39046	3603 SOUTHEASTERN PIEDMONT
42095	Northampton, PA	39048	3602 EAST CENTRAL MOUNTAINS
42101	Philadelphia, PA	39051	3603 SOUTHEASTERN PIEDMONT
42107	Schuylkill, PA	39054	3602 EAST CENTRAL MOUNTAINS
42125	Washington, PA	39063	3609 SOUTHWEST PLATEAU
42129	Westmoreland, PA	39065	3609 SOUTHWEST PLATEAU
42133	York, PA	39067	3604 LOWER SUSQUEHANNA
44003	Kent, RI	40002	3701 ALL

FIPS Code	Area Name	NCHS Code	Climate Division Code and Name
44007	Providence, RI	40004	3701 ALL
45003	Aiken, SC	41002	3805 WEST CENTRAL
45007	Anderson, SC	41004	3802 NORTHWEST
45019	Charleston, SC	41010	3807 SOUTHERN
45041	Florence, SC	41021	3804 NORTHEAST
45045	Greenville, SC	41023	3802 NORTHWEST
45051	Horry, SC	41026	3804 NORTHEAST
45063	Lexington, SC	41032	3806 CENTRAL
45079	Richland, SC	41040	3806 CENTRAL
45083	Spartanburg, SC	41042	3802 NORTHWEST
45091	York, SC	41046	3803 NORTH CENTRAL
46099	Minnehaha, SD	42049	3909 SOUTHEAST
47037	Davidson, TN	43019	4003 MIDDLE
47065	Hamilton, TN	43033	4001 EASTERN
47093	Knox, TN	43047	4001 EASTERN
47157	Shelby, TN	43079	4004 WESTERN
47163	Sullivan, TN	43082	4001 EASTERN
48027	Bell, TX	44014	4103 NORTH CENTRAL
48029	Bexar, TX	44015	4107 SOUTH CENTRAL
48039	Brazoria, TX	44020	4108 UPPER COAST
48061	Cameron, TX	44031	4110 LOWER VALLEY
48085	Collin, TX	44043	4103 NORTH CENTRAL
48113	Dallas, TX	44057	4103 NORTH CENTRAL
48121	Denton, TX	44061	4103 NORTH CENTRAL
48135	Ector, TX	44068	4105 TRANS PECOS
48141	El Paso, TX	44071	4105 TRANS PECOS
48157	Fort Bend, TX	44079	4108 UPPER COAST
48167	Galveston, TX	44084	4108 UPPER COAST
48201	Harris, TX	44101	4108 UPPER COAST
48215	Hidalgo, TX	44108	4110 LOWER VALLEY
48245	Jefferson, TX	44123	4108 UPPER COAST
48303	Lubbock, TX	44152	4101 HIGH PLAINS
48309	McLennan, TX	44155	4103 NORTH CENTRAL
48339	Montgomery, TX	44170	4104 EAST TEXAS
48355	Nueces, TX	44178	4107 SOUTH CENTRAL
48423	Smith, TX	44212	4104 EAST TEXAS
48439	Tarrant, TX	44220	4103 NORTH CENTRAL
48441	Taylor, TX	44221	4102 LOW ROLLING PLAINS
48453	Travis, TX	44227	4107 SOUTH CENTRAL
48485	Wichita, TX	44243	4102 LOW ROLLING PLAINS
49011	Davis, UT	45006	4205 NORTHERN MOUNTAINS
49035	Salt Lake, UT	45018	4203 NORTH CENTRAL
49049	Utah, UT	45025	4205 NORTHERN MOUNTAINS
49057	Weber, UT	45029	4205 NORTHERN MOUNTAINS
50007	Chittenden, VT	46004	4302 WESTERN
51510	Alexandria, VA	47003	4404 NORTHERN
51013	Arlington, VA	47008	4404 NORTHERN

FIPS Code	Area Name	NCHS Code	Climate Division Code and Name
51550	Chesapeake, VA	47026	4401 TIDEWATER
51041	Chesterfield, VA	47027	4402 EASTERN PIEDMONT
51059	Fairfax, VA	47040	4404 NORTHERN
51650	Hampton, VA	47058	4401 TIDEWATER
51087	Henrico, VA	47061	4402 EASTERN PIEDMONT
51700	Newport News, VA	47087	4401 TIDEWATER
51710	Norfolk, VA	47088	4401 TIDEWATER
51740	Portsmouth, VA	47099	4401 TIDEWATER
51153	Prince William, VA	47103	4404 NORTHERN
51760	Richmond, VA	47108	4402 EASTERN PIEDMONT
51810	Virginia Beach, VA	47127	4401 TIDEWATER
53005	Benton, WA	48003	4508 CENTRAL BASIN
53011	Clark, WA	48006	4504 E OLYMPIC CASCADE
53033	King, WA	48017	4503 PUGET SOUND LOWLANDS
53035	Kitsap, WA	48018	4503 PUGET SOUND LOWLANDS
53053	Pierce, WA	48027	4503 PUGET SOUND LOWLANDS
53061	Snohomish, WA	48031	4503 PUGET SOUND LOWLANDS
53063	Spokane, WA	48032	4509 NORTHEASTERN
53067	Thurston, WA	48034	4504 E OLYMPIC CASCADE
53073	Whatcom, WA	48037	4503 PUGET SOUND LOWLANDS
53077	Yakima, WA	48039	4508 CENTRAL BASIN
54039	Kanawha, WV	49020	4603 SOUTHWESTERN
55009	Brown, WI	50005	4706 EAST CENTRAL
55025	Dane, WI	50013	4708 SOUTH CENTRAL
55059	Kenosha, WI	50030	4709 SOUTHEAST
55073	Marathon, WI	50037	4702 NORTH CENTRAL
55079	Milwaukee, WI	50041	4709 SOUTHEAST
55087	Outagamie, WI	50045	4706 EAST CENTRAL
55101	Racine, WI	50052	4709 SOUTHEAST
55105	Rock, WI	50054	4708 SOUTH CENTRAL
55117	Sheboygan, WI	50060	4706 EAST CENTRAL
55133	Waukesha, WI	50068	4709 SOUTHEAST
55139	Winnebago, WI	50071	4706 EAST CENTRAL

Appendix 3. Rectification Notes

Adjustments to county FIPS codes to create spatially consistent areas through the study period are listed in the table below

FIPS Code	Area Name	NCHS Code	Rectification Notes
08005	Arapahoe, CO	06003	Part annexed to Denver Co in 1988
08031	Denver, CO	06016	Parts annexed to Arapahoe and Adams 1980
12025	Miami-Dade, FL	10013	12086 after 1997 (Date to Miami-Dade)
30113	Yellowstone National Park, MT	27057	Became part of Gallatin and Park in 1990
35006	Cibola, NM	32004	Separated from Valencia County in 1981
46071	Jackson, SD	42035	Washabaugh County Annexed 1983 to Jackson (42067)
48301	Loving, TX	44151	Loving Tx - small population. Some months without values
51001	Accomack, VA	47001	79–81 code recoded to 47003
51003	Albemarle, VA	47002	79–81 code recoded to 47006; part annexed to Charlottesville 1988
51005	Alleghany, VA	47004	79–81 code recoded to 47009
51007	Amelia, VA	47005	79–81 code recoded to 47012
51009	Amherst, VA	47006	79–81 code recoded to 47015
51011	Appomattox, VA	47007	79–81 code recoded to 47018
51013	Arlington, VA	47008	79–81 code recoded to 47021
51015	Augusta, VA	47009	79–81 code recoded to 47024; part annexed to Staunton 1986 and Waynesboro 1985
51017	Bath, VA	47010	79–81 code recoded to 47027
51019	Bedford, VA	47011	79–81 code recoded to 47030
51021	Bland, VA	47013	79–81 code recoded to 47033
51023	Botetourt, VA	47014	79–81 code recoded to 47036
51025	Brunswick, VA	47016	79–81 code recoded to 47039
51027	Buchanan, VA	47017	79–81 code recoded to 47042
51029	Buckingham, VA	47018	79–81 code recoded to 47045
51031	Campbell, VA	47020	79–81 code recoded to 47048
51033	Caroline, VA	47021	79–81 code recoded to 47051
51035	Carroll, VA	47022	79–81 code recoded to 47054
51036	Charles City, VA	47023	79–81 code recoded to 47057
51037	Charlotte, VA	47024	79–81 code recoded to 47060
51041	Chesterfield, VA	47027	79–81 code recoded to 47063
51043	Clarke, VA	47028	79–81 code recoded to 47066
51045	Craig, VA	47032	79–81 code recoded to 47069
51047	Culpeper, VA	47033	79–81 code recoded to 47072
51049	Cumberland, VA	47034	79–81 code recoded to 47075
51051	Dickenson, VA	47036	79–81 code recoded to 47078
51053	Dinwiddie, VA	47037	79–81 code recoded to 47081
51057	Essex, VA	47039	79–81 code recoded to 47084
51059	Fairfax, VA	47040	79–81 code recoded to 47087; part annexed to Fairfax City 1980
51061	Fauquier, VA	47043	79–81 code recoded to 47090

FIPS Code	Area Name	NCHS Code	Rectification Notes
51063	Floyd, VA	47044	79–81 code recoded to 47093
51065	Fluvanna, VA	47045	79–81 code recoded to 47096
51067	Franklin, VA	47046	79–81 code recoded to 47099
51069	Frederick, VA	47048	79–81 code recoded to 47102
51071	Giles, VA	47051	79–81 code recoded to 47105
51073	Gloucester, VA	47052	79–81 code recoded to 47108
51075	Goochland, VA	47053	79–81 code recoded to 47111
51077	Grayson, VA	47054	79–81 code recoded to 47114
51079	Greene, VA	47055	79–81 code recoded to 47117
51081	Greensville, VA	47056	79–81 code recoded to 47120; part annexed to Emporia 1988.
51083	Halifax, VA	47057	79–81 code recoded to 47123
51085	Hanover, VA	47059	79–81 code recoded to 47126
51087	Henrico, VA	47061	79–81 code recoded to 47129
51089	Henry, VA	47062	79–81 code recoded to 47132
51091	Highland, VA	47063	79–81 code recoded to 47135
51093	Isle of Wight, VA	47065	79–81 code recoded to 47138
51095	James City, VA	47066	79–81 code recoded to 47141; part annexed to Williamsburg 1983
51097	King and Queen, VA	47067	79–81 code recoded to 47144
51099	King George, VA	47068	79–81 code recoded to 47147
51101	King William, VA	47069	79–81 code recoded to 47150
51103	Lancaster, VA	47070	79–81 code recoded to 47153
51105	Lee, VA	47071	79–81 code recoded to 47156
51107	Loudoun, VA	47073	79–81 code recoded to 47159
51109	Louisa, VA	47074	79–81 code recoded to 47162
51111	Lunenburg, VA	47075	79–81 code recoded to 47165
51113	Madison, VA	47077	79–81 code recoded to 47168
51115	Mathews, VA	47081	79–81 code recoded to 47171
51117	Mecklenburg, VA	47082	79–81 code recoded to 47174
51119	Middlesex, VA	47083	79–81 code recoded to 47177
51121	Montgomery, VA	47084	79–81 code recoded to 47180
51125	Nelson, VA	47085	79–81 code recoded to 47186
51127	New Kent, VA	47086	79–81 code recoded to 47189
51131	Northampton, VA	47089	79–81 code recoded to 47195
51133	Northumberland, VA	47090	79–81 code recoded to 47198
51135	Nottoway, VA	47092	79–81 code recoded to 47201
51137	Orange, VA	47093	79–81 code recoded to 47204
51139	Page, VA	47094	79–81 code recoded to 47207
51141	Patrick, VA	47095	79-81 code recoded to 47210
51143	Pittsylvania, VA	47097	79–81 code recoded to 47213; part annexed to Danville 1987
51145	Powhatan, VA	47100	79–81 code recoded to 47216
51147	Prince Edward, VA	47101	79–81 code recoded to 47219
51149	Prince George, VA	47102	79–81 code recoded to 47222
51153	Prince William, VA	47103	79–81 code recoded to 47225; part annexed to Manassas 1983
51155	Pulaski, VA	47104	79–81 code recoded to 47231
51157	Rappahannock, VA	47106	79–81 code recoded to 47234
51159	Richmond, VA	47107	79–81 code recoded to 47237

FIPS Code	Area Name	NCHS Code	Rectification Notes
51161	Roanoke, VA	47109	79–81 code recoded to 47240
51163	Rockbridge, VA	47111	79–81 code recoded to 47243; part annexed to Buena Vista 1985
51165	Rockingham, VA	47112	79–81 code recoded to 47246; part annexed to Harrisonburg 1982
51167	Russell, VA	47113	79–81 code recoded to 47249
51169	Scott, VA	47115	79–81 code recoded to 47252
51171	Shenandoah, VA	47116	79–81 code recoded to 47255
51173	Smyth, VA	47117	79–81 code recoded to 47258
51175	Southampton, VA	47118	79–81 code recoded to 47261; part annexed to Southhampton 1985
51177	Spotsylvania, VA	47120	79–81 code recoded to 47264; part annexed to Fredericksburg 1983
51179	Stafford, VA	47121	79–81 code recoded to 47267
51181	Surry, VA	47124	79–81 code recoded to 47270
51183	Sussex, VA	47125	79–81 code recoded to 47273
51185	Tazewell, VA	47126	79–81 code recoded to 47276
51187	Warren, VA	47128	79–81 code recoded to 47279
51191	Washington, VA	47129	79–81 code recoded to 47282
51193	Westmoreland, VA	47131	79–81 code recoded to 47285
51195	Wise, VA	47134	79–81 code recoded to 47288
51197	Wythe, VA	47135	79–81 code recoded to 47291
51199	York, VA	47136	79–81 code recoded to 47294
51510	Alexandria, VA	47003	79–81 code recoded to 47300
51515	Bedford, VA	47012	79–81 code recoded to 47303
51520	Bristol, VA	47015	79–81 code recoded to 47306
51530	Buena Vista, VA	47019	79–81 code recoded to 47309
51540	Charlottesville, VA	47025	79–81 code recoded to 47312
51550	Chesapeake, VA	47026	79–81 code recoded to 47315
51560	Clifton Forge, VA	47029	79–81 code recoded to 47318; del to Alleghany 2001
51570	Colonial Heights,	47030	79–81 code recoded to 47321
51580	Covington, VA	47031	79–81 code recoded to 47324
51590	Danville, VA	47035	79–81 code recoded to 47327
51595	Emporia, VA	47038	79–81 code recoded to 47330
51600	Fairfax, VA	47041	79–81 code recoded to 47333
51610	Falls Church, VA	47042	79–81 code recoded to 47336
51620	Franklin, VA	47047	79–81 code recoded to 47339
51630	Fredericksburg, VA	47049	79–81 code recoded to 47342
51640	Galax, VA	47050	79–81 code recoded to 47345
51650	Hampton, VA	47058	79–81 code recoded to 47348
51660	Harrisonburg, VA	47060	79–81 code recoded to 47351
51670	Hopewell, VA	47064	79–81 code recoded to 47354
51678	Lexington, VA	47072	79–81 code recoded to 47357
51680	Lynchburg, VA	47076	79–81 code recoded to 47360
51683	Manassas, VA	47078	Coded as Prince William through 81
51685	Manassas Park, VA	47079	Coded as Prince William through 81
51690	Martinsville, VA	47080	79–81 code recoded to 47363
51700	Newport News, VA	47087	79–81 code recoded to 47366

FIPS Code	Area Name	NCHS Code	Rectification Notes
51710	Norfolk, VA	47088	79–81 code recoded to 47369
51720	Norton, VA	47091	79–81 code recoded to 47372
51730	Petersburg, VA	47096	79–81 code recoded to 47375
51735	Poquoson, VA	47098	Coded as York through 81
51740	Portsmouth, VA	47099	79–81 code recoded to 47378
51750	Radford, VA	47105	79–81 code recoded to 47381
51760	Richmond, VA	47108	79–81 code recoded to 47384
51770	Roanoke, VA	47110	79–81 code recoded to 47387
51775	Salem, VA	47114	79–81 code recoded to 47390
51780	South Boston, VA	47119	79–81 code recoded to 47393; part of Halifax 1995
51790	Staunton, VA	47122	79–81 code recoded to 47396
51800	Suffolk, VA	47123	79–81 code recoded to 47399
51810	Virginia Beach, VA	47127	79–81 code recoded to 47402
51820	Waynesboro, VA	47130	79–81 code recoded to 47405
51830	Williamsburg, VA	47132	79–81 code recoded to 47408
51840	Winchester, VA	47133	79–81 code recoded to 47411

Vita

Mike Meyers was born to Peter and Kathleen Meyers on a farm in northeast Oregon. He is the oldest of a family of five boys and one girl. He is also the proud father of three sons. As his father once remarked, “Girls are hard to come by in this family.” These facts have conspired to engage him in the study of sex ratio variation near the end of a career that began with work as a farmhand, social worker, taxi driver, mechanic and other jobs designed to pad the dust jacket resume on a first novel that never materialized.

He has worked as a regional planner and environmental manager for the Department of Interior in Oregon and Washington and as an environmental consultant in Tennessee. He is currently employed by the University of Tennessee Institute for Public Service as a GIS consultant for local governments in Tennessee. He lives in a fine climate in the city of Maryville, Tennessee.