*New Title?: Graphical Data Analysis on the Circle: Wrap-around Time Series Plots for (Interrupted) Time Series Designs*

Wrap-around Time Series Plots (WATS Plots) for Interrupted Time Series Designs:

Applications to Fertility Rates and the Oklahoma City Bombing

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Abstract

*Many data structures, particular time series data, are naturally seasonal, cyclical, or otherwise circular. Past graphical methods for time series have focused on linear plots. In this paper, we move graphical analysis onto the circle. We focus on two methods, one old and one new. Rose diagrams are circular histograms, and can be produced in several different forms using the RRose software system. In addition, w*e propose, develop, and illustrate a new circular graphical method, called Wrap-Around Time Series Plots (WATS plots) that is useful to support time series analyses *in general*, *but in* particular in relation to interrupted time series designs. We illustrate the use of WATS Plots from an interrupted time series design evaluating the effect of the Oklahoma City bombing on birth rates in Oklahoma County during the ten years surrounding the bombing of the Murrah Building in Oklahoma City. We compare WATS Plots to linear time series representations with smoothing. Each method is shown to have advantages in relation to the other; *in our example,* the WATS Plots more clearly show the existence and effect size of the fertility differential.

Keywords: time series, interrupted time series design, group differences, graphical analysis, circular data, H-spread

Introduction

*During the past half century, and especially since the publication of Tukey's (1977) Exploratory Data Analysis, new graphical methods have been developed to facilitate exploratory analysis and to support interpretations in confirmatory settings. Some graphical methods are quite old; Wainer (2000) documented excellent graphs produced historically, including Playfair's work in the 18th century, and even before. Other methods are both new and novel, including the development by Tukey of stem-and-leaf diagrams and boxplots, and Cleveland's (1992) multi-way dot plots and conditional plots. In each case, the new graphical method is motivated by its ability to portray features of data that were not otherwise clear and/or apparent. As Tukey emphasized, no graph (or other statistical model) can accommodate all statistical goals: "Approximately: There is no more reason to expect one plot to adequately portray the data than to expect one number to do so.” In this paper, we present and develop circular graphical methods that are useful in plotting time series data.*

Cyclical patterns are often plotted linearly on the number line (for example, as histograms or dot plots with month on the horizontal axis). There are obvious advantages to such plots, including interpretability, convention, and software availability, among others. *Time series data are naturally cyclical, because of the daily, weekly, yearly, or other patterns that may (or may not) be built into such data. Circular graphical methods have both advantages and disadvantages relative to linear methods.*  We do not propose to replace linear methods with this new approach, but rather (*in the spirit of Tukey's quote above)* suggest that the two methods in combination provide substantial advantages compared to each one separately. *We briefly discuss several previous circular graphical methods, in particular the rose diagram. We then focus in more detail on a relatively new method, called Wrap Around Time Series Plots (WATS Plots).*

We motivate the use and value of WATS plots with reference to time series data already analyzed in Rodgers, St. John & Coleman (2005), who relied on standard linear methods for graphical presentation. We motivate the *need for circular methods* by reviewing graphical results from this previous study. We then review previous graphical methods used in time series analysis*, with focus on rose diagrams.* Next, we present and explain our new method. We present the typical linear and the new circular plots together, which illustrates advantages of each, *and complementarity between the two*. *We conclude by illustrating other research applications within behavioral science (and other) settings that might be facilitated by use of the WATS Plots.*

Motivating Example

A linear time series plot from Rodgers, St. John, and Coleman (2005) is shown in Figure 1. The outcomes in this plot are monthly birth rates (General Fertility Rates, GFR's) in Oklahoma County (the metropolitan county where Oklahoma City is located), between January, 1990 and December, 1999. In April, 1995, the Murrah Federal Building in Oklahoma City was bombed, resulting in 168 deaths, including several babies and young children in the building day care. Several studies have suggested that both natural and man-made disasters can lead to increases in birth and marriage rates, and decreases in divorce rates, and these effects can be of relatively long duration (see, e.g., Cohen & Cole 2002; Cohen, Cole, & Shoen 2009; Hansel, Nakonezny, & Rodgers 2011; Nakonezny, Rodgers, & Reddick 2004; also see Tong, Zotti, & Hsia 2011, for data containing a decreasing trend in birth rates following a natural disaster).

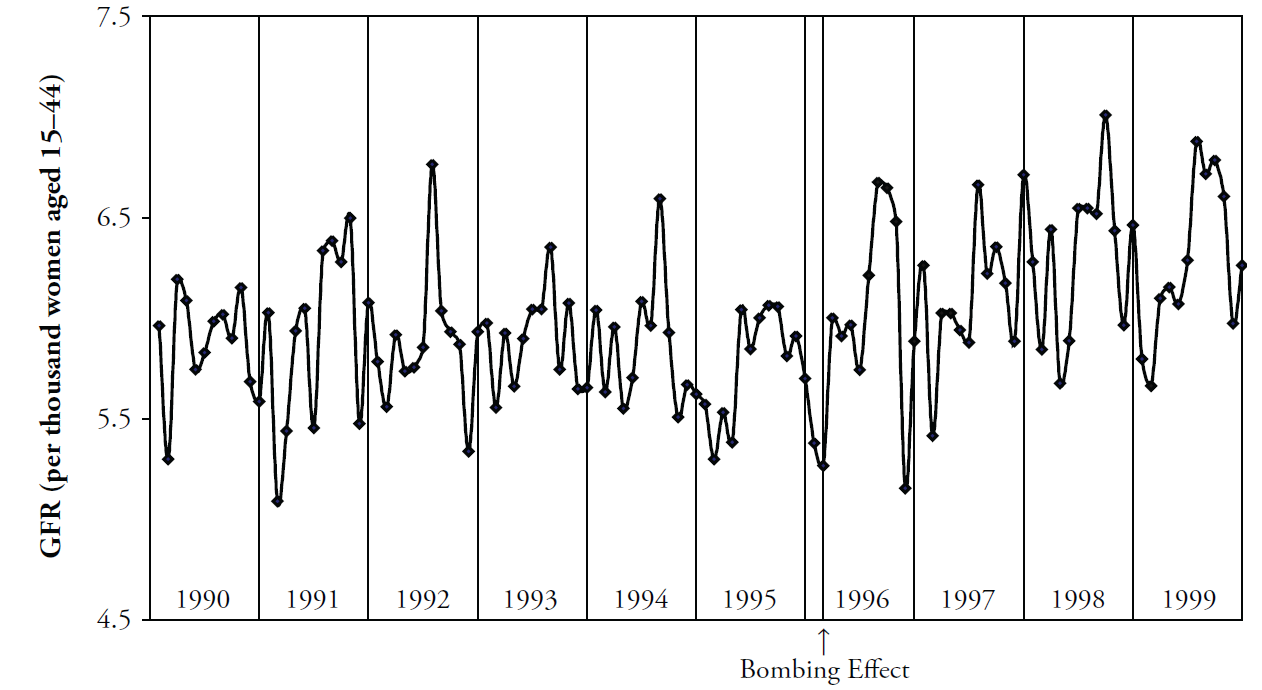


Figure 1: Raw monthly birth rates (General Fertility Rates; GFR's) for Oklahoma County, 1990-1999, plotted in a linear plot; the "bombing effect" is located ten months after

the Oklahoma City bombing

The original purpose of the linear plot in Figure 1 was to support the statistical evaluation of a *potential* effect of the Oklahoma City bombing on birth rates in Oklahoma County and several surrounding counties. According to Cook and Campbell (1979, p. 207), "*Interrupted* time-series analysis requires knowing the specific point in the series when a treatment occurred. The purpose of the analysis is to infer whether the treatment had any impact" (italics in original). This is exactly the situation in the Oklahoma City bombing study; the authors wished to infer whether the Oklahoma City bombing, the "treatment," had an impact on subsequent birth rates. Cook and Campbell (also see Shadish, Cook, & Campbell, 2002) devoted two chapters to interrupted time series analysis, including careful treatment of slope changes, intercept changes, and lagged effects. *Notably, all of their graphical portrayals were linear.* More broadly, many statistical methods exist to study time series patterns in weather, business, behavioral science, and many other areas. Autoregressive integrated moving average and related models, which were originally developed by Box and Jenkins (1970) have been popular. Our concern in the current paper is with the exploratory evaluation of interrupted time series data using graphical analysis and visual inspection. Such graphical analysis can be useful as a support tool for statistical modeling, or to suggest models and theories to further investigate.

Within Figure 1 is an indicator of February, 1996; this month, which followed ten months after the Oklahoma City bombing, was the earliest that meaningful pregnancy patterns after the bombing could be expected to occur. We invite the reader to study Figure 1, and determine visually whether a change in birth rates did occur following February, 1996. Because monthly birth rates at the county level are generally highly variable, as in Figure 1, this assessment may be difficult in relation to the GFR rates. To facilitate this inspection, Rodgers et al. (2005) passed a *graphical smoothing* model through the data in Figure 1, a 12-month running mean smoother. In Figure 2, we present three re-portrayals of their original figure, using mean smoothers *in the top and middle portrayals*, and a smoothed H-spread band *in the bottom graph* (*methodological details will be presented in a later section)*. The blue/green smoother *in the middle plot* is the 12-month running mean. The red smoother *in the first plot* only smooths the February points (averaging each February and the previous 11 months of GFR's), then connects those points (resulting in a smoother fit). Other methods were also inspected (e.g., spline smoothing, median smoothing, and various loess curves), which provided comparable improvement in visual clarity. Specifically, an increase in births rates can be seen beginning at exactly the month of interest, February, 1996, supporting that a systematic increase in births in Oklahoma County following the Oklahoma City bombing started ten months after the bombing and then persisted for several years.

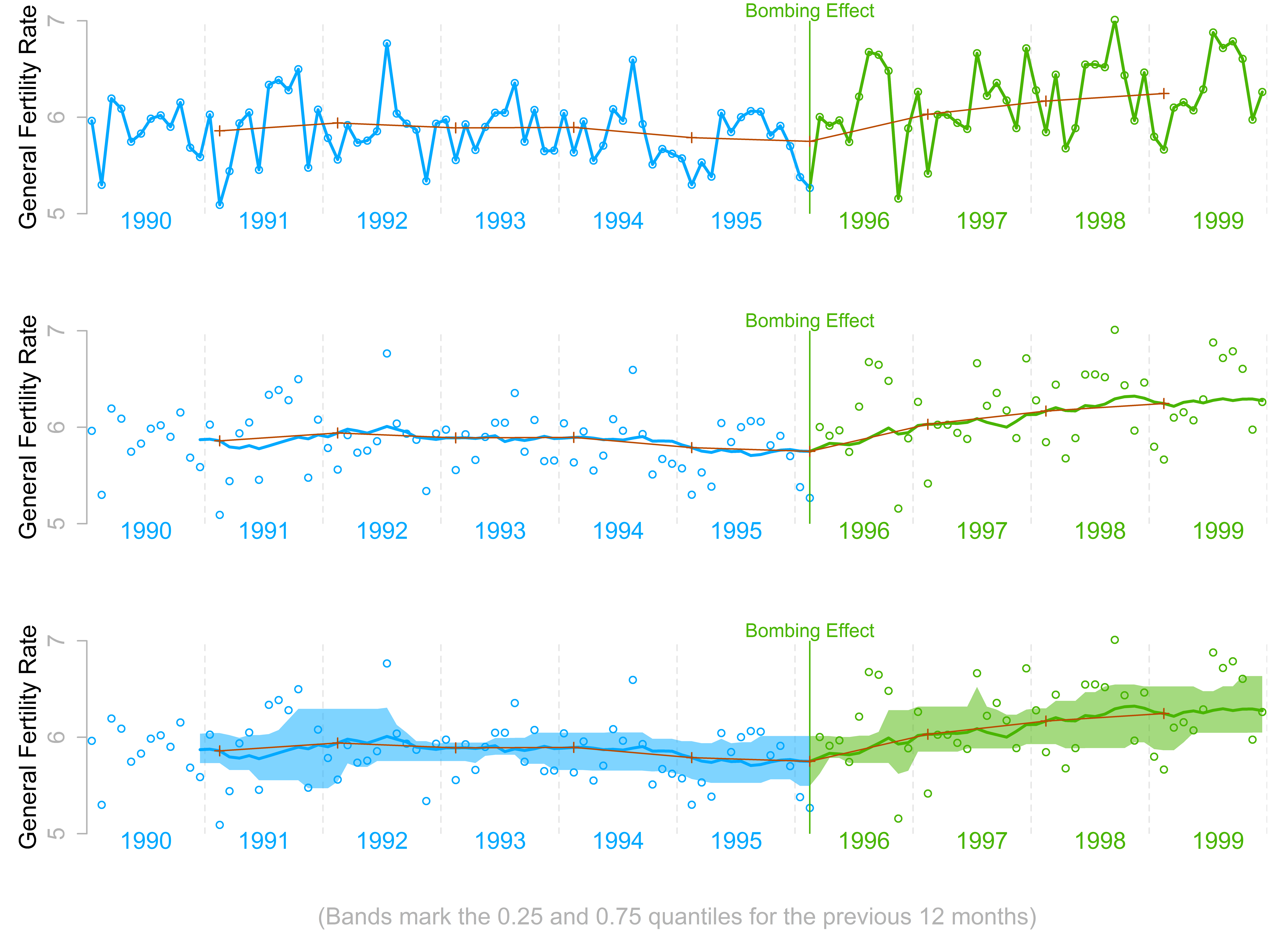


Figure 2: Smoothed monthly birth rates (General Fertility Rates; GFR's) for Oklahoma County, 1990-1999, plotted in a linear plot. *The top plot shows the connected raw data with a February smoother; the middle plot shows smoothing with a 12-month moving average, blue/green line, superimposed on a February smoother, red line); the bottom plot shows the smoothers and confidence bands,* which are H-spreads defined using the distribution of GFR's for the given month and 11 previous months.

*Rodgers, St. John, and Coleman (2006) also presented plots and time series analyses of nine other metropolitan counties in Oklahoma. These counties acted as control counties in relation to Oklahoma County, where the bombing occurred, in several different ways. Fertility data from one [??? Two???] other metropolitan counties will also be presented, along with the data from Oklahoma County, to provide broader illustration of the features of the methods developed in the current paper. Readers interested in the substantive results of this analysis, or in the methodological details associated with it, are directed to the original 2006 article.*

A weakness of the portrayals in Figures 1-2, and in other portrayals of time series data on the number line, is that the cyclical or seasonal nature of such data cannot be easily represented or observed. For example, in virtually all time series datasets representing birth patterns, there are seasonal patterns in those data (see, e.g., Seiver 1985; Rodgers & Udry 1988; Lam and Miron 1991). In Figures 1 and 2, the seasonal birth patterns can be seen at the extremes; for example,

most of the highest GFR's occur in either August or September, although it takes some time and careful inspection to determine that.

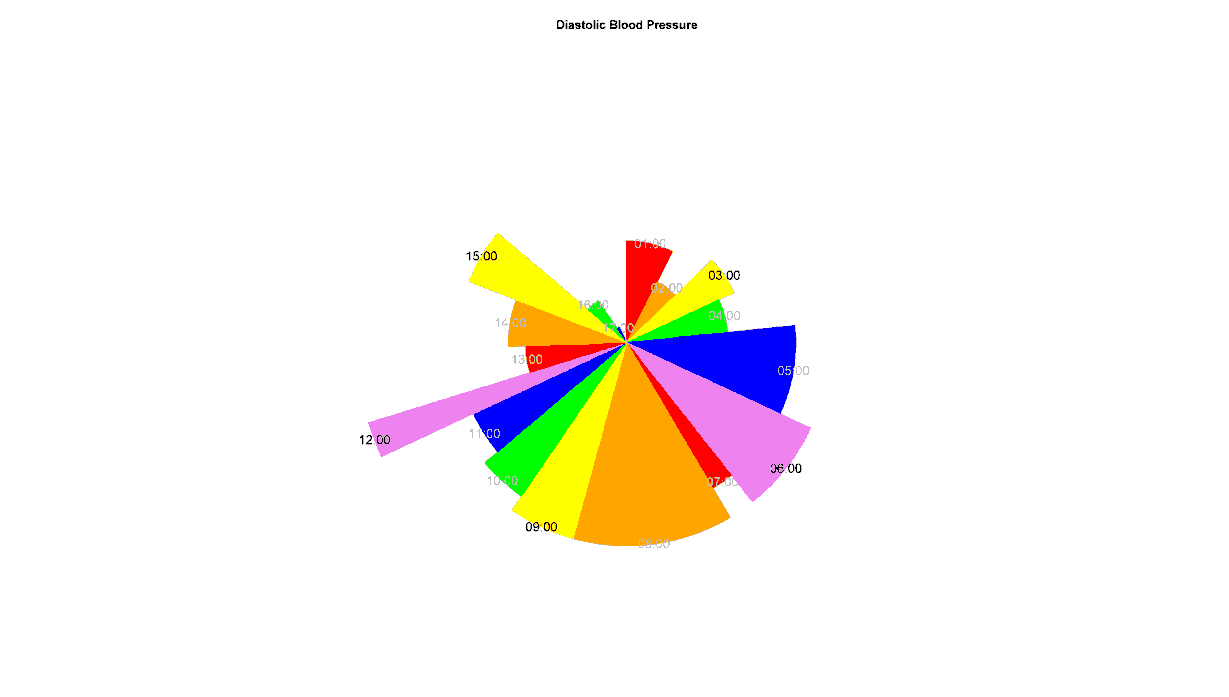
Previous Graphical Methods to Portray Time Series

A number of linear graphical methods have been developed to use in time series settings. Correlograms are used to portray autocorrelation structure graphically, and periodograms fit a spectral smoother to time series data (these were originally proposed by Schuster in 1898; see Shumway & Stoffer, 2010, for modern treatment). A number of more recent smoothing methods are routinely used in time series analysis, including mean- and median-smoothing, spline smoothing, and kernel smoothing. One of the most popular, flexible, and powerful linear smoothing methods (useful in time series, and also in many other scatterplot settings) is Cleveland's locally optimal scatterplot smoothing, which produces loess curves. Cleveland (1993) provides general review of these smoothing methods. Software implementation in interactive graphic mode of these smoothing methods is easily implemented in statistical software packages such as SAS and R. In each of these linear plots, the eye is carried across the page, observing changes in the time series from left to right.

The advantages of software support and traditional interpretation is balanced against several disadvantages. First, plotting time series across many years on a linear plot can be prohibitive of space (e.g., see Kohler, Rodgers, & Christensen, 1999, who portrayed almost 100 years of fertility data at the yearly level; *major features of the patterns were revealed, but virtually all details were lost*). Second, and perhaps most importantly, seasonal (e.g., monthly) trends are difficult to see in linear time series plots. Third, if linear data are averaged into a single plot, the 12-month cycle necessarily separates two months (December and January) that visually appear to be far apart, but which are in fact temporally contiguous. Fourth, and of particular relevance to motivate the current article, it is difficult in linear plots to portray and to visualize time series interruptions or group differences of any type, especially across separate time periods (*see Figure 1, for example)*. These comments motivate the idea of wrapping a linear plot around a circle to portray time series patterns. This method has been used in several different ways in the past.

A well-known and popular method to accommodate cyclical, seasonal, or circular frequencies is the use of the rose diagram. This method was invented by Florence Nightingale to plot mortality patterns by month during the Crimean War; see Wainer (2000) for background. The rose diagram (Nightingale called them "coxcombs") wraps the histogram around a circle. This representation uses angles rather than intervals along the number line to represent the levels of the explanatory variable (usually time). Quantitative information reflected in the levels of the explanatory variable can be also represented by allowing the angles to vary; in monthly time series data, the angels are fixed at 30 degrees (1/12 of the circle). Interpretational challenges with rose diagrams exist, associated with the proper cognitive representation of the height of histograms (which expand disproportionately the further from the center of the circle). But the advantage of rose diagrams is that they properly account for the cyclical nature of seasonal/ circular data. In particular, December is located contiguous to January, rather than as far away as possible. Rodgers and Udry (1988) presented rose diagrams of national-level U.S. birth data and of college students’ monthly preferences for giving birth.1

The third author of this paper has developed a software system to represent rose diagrams. The Java implementation of the system is called jRose, and the R implementation is called RRose. The software and instructions can be obtained from the website <http://endaemon.com/rose>. The program will take time series data as input, and produce a standard rose diagram in color. Alternatively, in the spirit of Tufte's (2000) entreaty to optimize the data-ink ratio, the system will also produce so-called "Tufterized rose diagrams" by eliminating most of the ink and retaining the arcs that describe the values of the outcome, and the angles of the explanatory variables. We provide two simple illustrations. In Figure ??, we present an RRose presentation of diastolic blood pressure collected by the third author over a 24-hour period. The angles reflect the intervals between data collection, and the lengths of the “petals” show the blood pressure. In Figure ??b, a ”Tufterized rose diagram” is presented for the same data, in which the amount of ink is minimized.



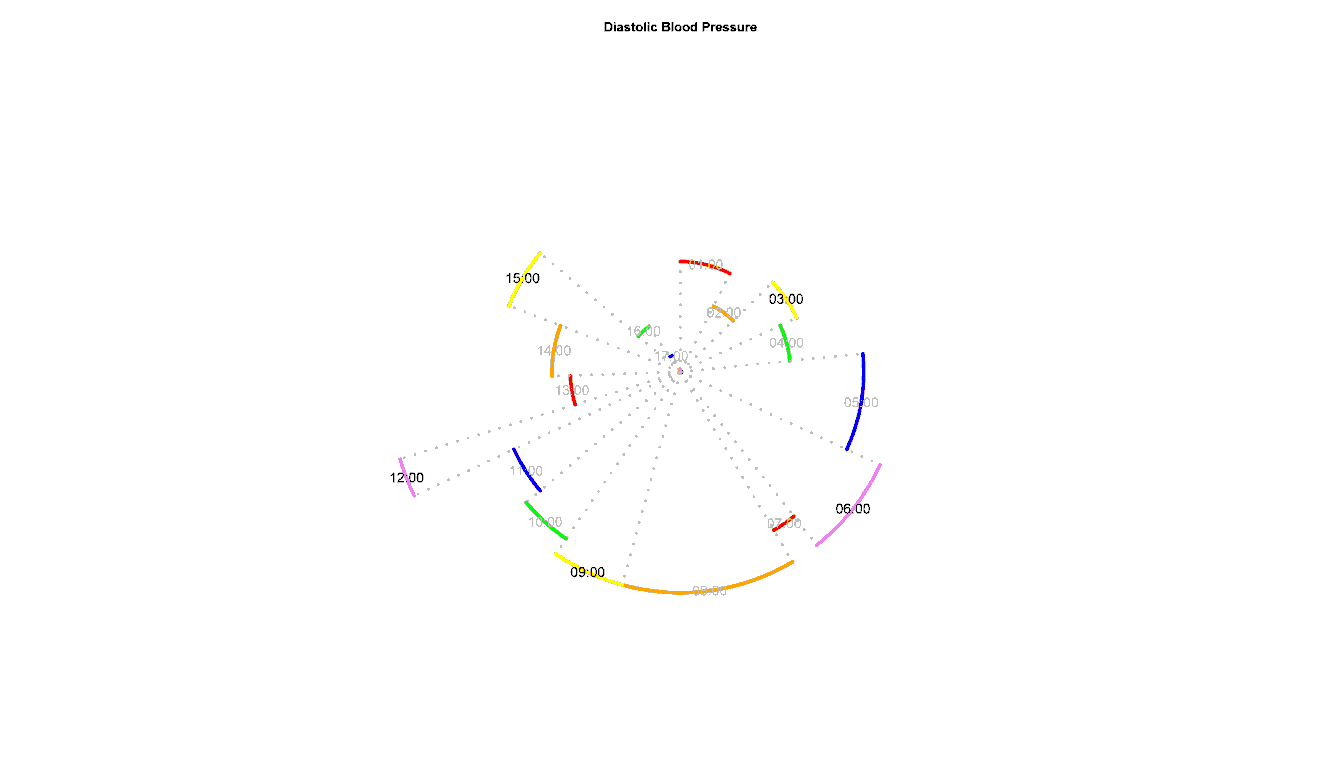


Figure 3a and 3b: Rose diagrams (regular in 3a and “Tufterized” in 3b), produced with JRose/RRose software, diastolic blood pressure measured for one individual over the course of a 24-hours period; angles reflect measurement intervals, length of petals show measured blood pressure

A recent book presents a number of methods to portray time series data, several of which also help motivate the use of WATS plots. Wills (2010, p. 34) showed a linear time series graph of monthly wind speeds in Ireland, with a 95% confidence interval superimposed to show both local and general stability of the trends. Then, he presented (p. 54) time series patterns of sea and air temperatures during El Nino that show the distribution of temperatures during each month as boxplots wrapped around the circle; on the same page are also presented linear plots, which show similar structure but suggest different visual interpretations. Finally, he presented (p. 128) a graph that wraps the data patterns around the circle, similar to the WATS plots, to portray business "layoff data" over an 11-year period from 1998 to 2008. He justified the plot as follows: "This version is more compact than the linear version, and it visually appears more like a single entity, which makes the chart easier to compare to other similar charts." Our presentation expands that of Wills by considering the graphical presentation of group differences and interrupted time series, and also expanding the treatment of confidence intervals beyond his treatment.

WATS Plots

We present here a method for graphing time series data on a circle. Our method has relationships to rose diagrams and to the "wind rose" charts developed by Lalanne (1830), which preceded Nightingale's rose diagrams (see Friendly 2007; Wainer 2000), and also to the (unnamed) plot presented in Wills (2010) and described above. We refer to our method as "Wrap-Around Time Series" plots, or in the acronym, WATS Plots. In WATS Plots, raw or smoothed data, and confidence bands, are wrapped around a circle. Whereas a rose diagram can be described as a circular histogram, a general version of the WATS Plot is closer in concept to a circular frequency polygon (or, once augmented with H-Spread confidence bands, as an expanded circular boxplot). Of particular value is that multiple years can be wrapped around the circle in a WATS Plot, whereas a rose diagram typically only shows one year, or shows an average circular histogram. (Nightingale showed two years of mortality data by drawing a dotted line between two different rose diagrams; see Wainer, 2000 to view the original wind rose and Nightingale rose diagrams.) Because multiple years (or other cycles) can be wrapped around the circle, WATS Plots are particularly valuable to evaluate the quantitative effect of an intervention, or other group differences, as we will demonstrate in the next section. *However, we emphasize that their use in interrupted time series designs is only one of many potential applications; we discuss these further in the Discussion.*

*Software implementation of WATS Plots can be facilitated through an R package that is available on the Comprehensive R Archival Network (CRAN): URL HERE. Code, documentation, and examples are included on that website, to support researchers who wish to develop WATS Plots for their own research purposes.*

Creating WATS Plots

Like many graphical methods, the basic WATS Plot emerges from a very simple idea, to wrap the frequency polygon around a circle so that distance from the center reflects frequency. *The ideas for the stem-and-leaf diagram and boxplot were similarly simple, but following Tukey's original development, these have been expanded in many different ways (including back-to-back stem and leaf diagrams, notched boxplots, using boxplots as coordinate axes, etc.). Similarly, there are many variations of the basic idea of the WATS Plot that can facilitate the graphical production and presentation of the WATS Plots. We present several of those here; there are undoubtedly others that creative graph-makers can develop in addition to the ones that we present.*

First, because the lines can overlap and become difficult to distinguish visually if there are many years portrayed, using color can help in the presentation of WATS Plots. For example, if presenting 15 years of monthly data, yellow can be used for the first 5 years, purple for the next five years, and green for the last five (these colors are selected because on the spectral dimension they are far apart, and in fact can even be distinguished by most color-blind viewers); of course interactive trial-and-error are useful to create *color within* plots that achieve the graph-makers' purpose. Second, boxplots can be superimposed over the lines, *within each angular category and extending out from the origin,* to give visual comparison of the distributional structure at each month (or whatever relevant unit is represented by the angles). Third, there are various methods to superimpose parametric or nonparametric confidence intervals over the lines themselves; ultimately, the lines connecting data points may be superfluous and may be eliminated if the confidence bands effectively portray the time series structure. *We elaborate on this third enhancement, and illustrate it later in the paper.*

The creation of the confidence bands includes several difference approaches. First, each month (or other unit) can be viewed separately, with a parametric 95% confidence interval *defined across the replications within that category*. Alternatively, the inter-quartile range, or H-Spread, which accounts for the middle 50% of the distribution, can be defined for each angular unit. Second, a smoothing method may be passed across the months, such that each confidence interval or H-Spread band may reflect (say) the month on which it is centered and the two months surrounding it on each side. Third, group or time differences may be accounted for as separate CIs or H-Spread bands. *This latter approach is especially useful within interrupted time series graphs, as separate H-Spread bands (or parametric CI's) can be defined for the period before and after the interruption.*

Several of these innovations are included within the R package that supports this article. *Researchers may simply apply the methods built into the online package; examples later within this article illustrate the results. Alternatively,* data analysts facile with R (or SAS, or Stata) can program these and other innovations to enhance WATS plots as they wish.

Motivating Example: Continued

We now return to the motivating example to illustrate the construction of WATS Plots, to compare them to linear frequency polygons and other time-series plots, and to illustrate their value in addressing an actual research problem involving group differences. First, we present in Figure 4 a re-portrayal of the raw GFR's presented in a linear plot in Figure 1. In this figure, pre-bombing fertility is represented in blue, and post-bombing in green. Without the smoother, it is difficult to visually detect increasing birth patterns that occur after the bombing.

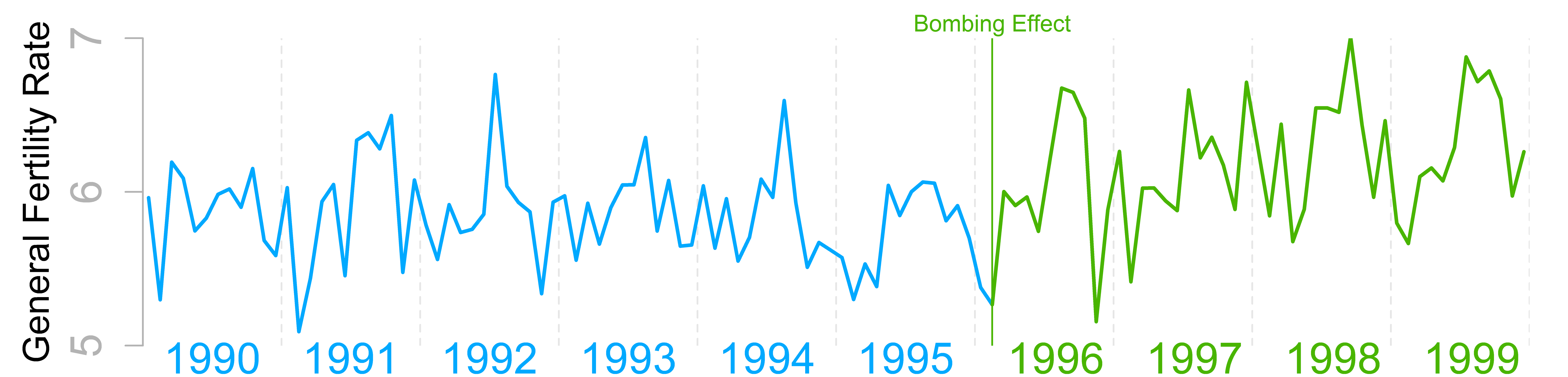


Figure 4: Re-portrayal of the linear plot of the GFR time series in Oklahoma County

To further develop this plot, we superimpose robust confidence intervals on the plot (see Figure 5). These CI's are defined as "H-spread bands" (Tukey 1977, p. 44) and both the blue and the green H-spread bands are superimposed on each side of the plot so that they can be compared. These H-spread bands are H-spreads defined within month categories, separately for the months before and the months after the bombing. *More specifically, we defined an h-spread from the distribution of six pre-bombing January GFR's, attached to the h-spread for the six pre-bombing February GFR's, etc. The resulting H-Spread band is then repeated for each year. The same procedure is used to across the four post-bombing GFR's for each month.* It can be clearly seen in this portrayal that the middle half of the distribution of fertility rates after the bombing is typically higher than the middle half of the rates before the bombing. The WATS Plot will show this effect in a different way, and even more vividly. In Figure 6, we present the WATS Plot version of the raw GFR data. There are ten yearly cycles superimposed within this plot, slightly over six in blue and slightly under four in green. In Figure 6, it is even more clear how the GFR fertility rates increased following the Oklahoma City bombing, despite the difficulty of detecting the effect visually in Figures 1 and 3.

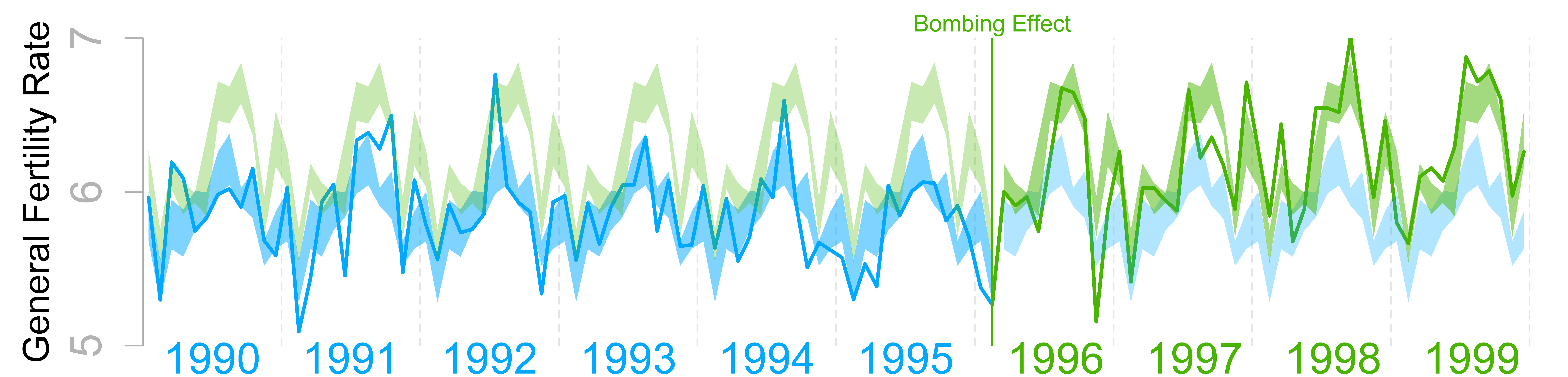


Figure 5: Linear plot of the GFR time series data in Oklahoma County, with H-spread Bands superimposed

In Figure 7, we add several elaborations that summarize and illustrate the full development. On the top left is the WATS Plot with the H-spread bands superimposed on top of the data. In the top right is a plot in which the data lines have been deleted, so that only the H-spread bands from the before-bombing and after-bombing distributions are shown. This plot vividly shows how clearly the bombing influenced fertility. The two H-spreads rarely overlap for any month. Further, the distance between the blue and green bands can be viewed as a visual effect size. At the bottom we show the original linear plot. The combination of the two provides an elaborate representation of the birth patterns in Oklahoma County before and after

the bombing. The linear plot does a better job of showing how the patterns change through time, as the eye is drawn from left to right across the graph. The WATS Plot does a better job of showing the difference in the before- and after-bombing patterns, effectively portraying the effect of the interruption in the time series. Aggregate differences can be seen in the WATS Plot, or differences within months -- which are lined up in the WATS Plot -- can be studied. We also note that the birth seasonality patterns are clearly visible in the WATS Plots (note the bulge out around September, and the dip in around April; these are the monthly birth peaks and valleys found in virtually all U.S. birth distributions).

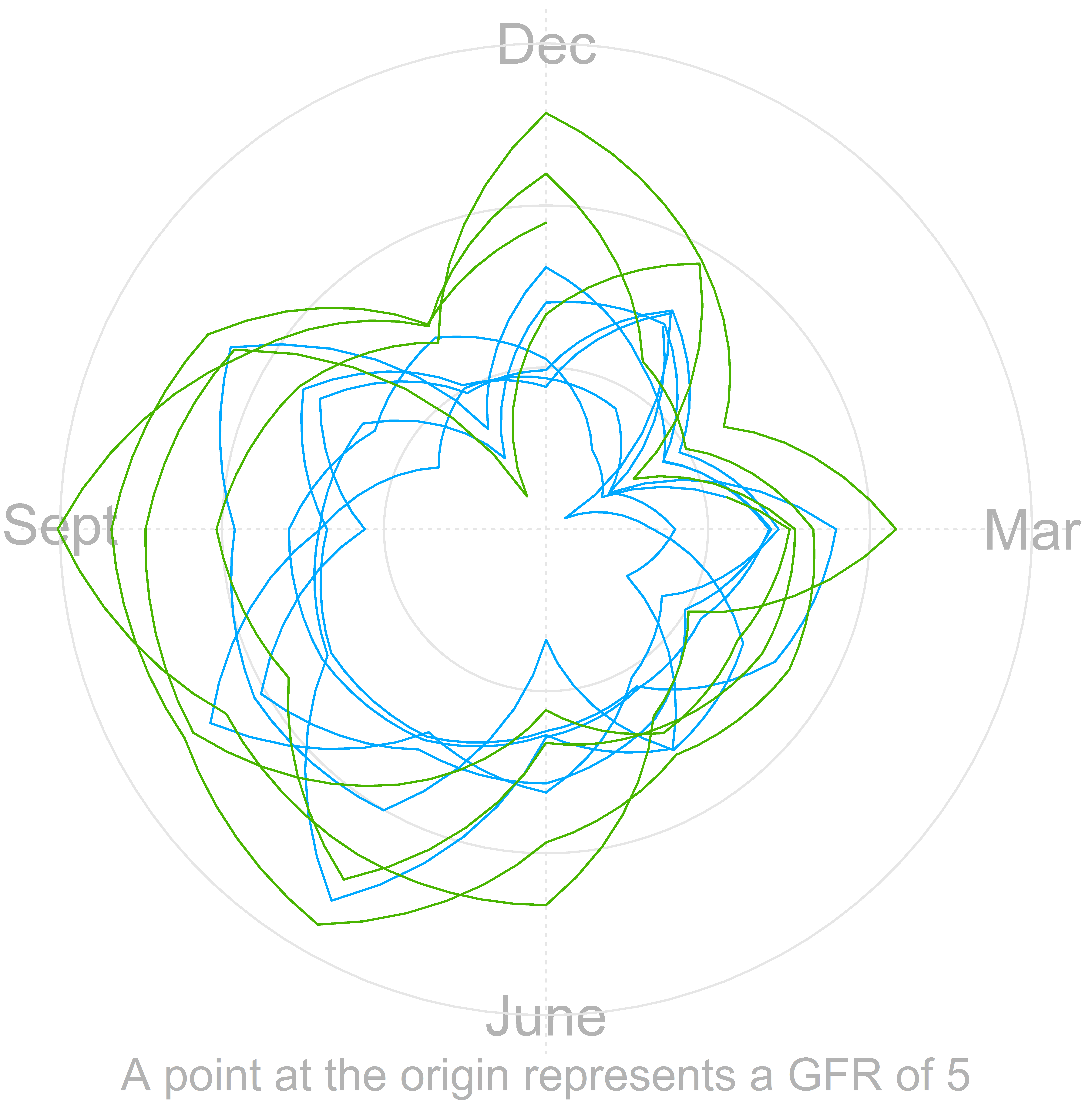
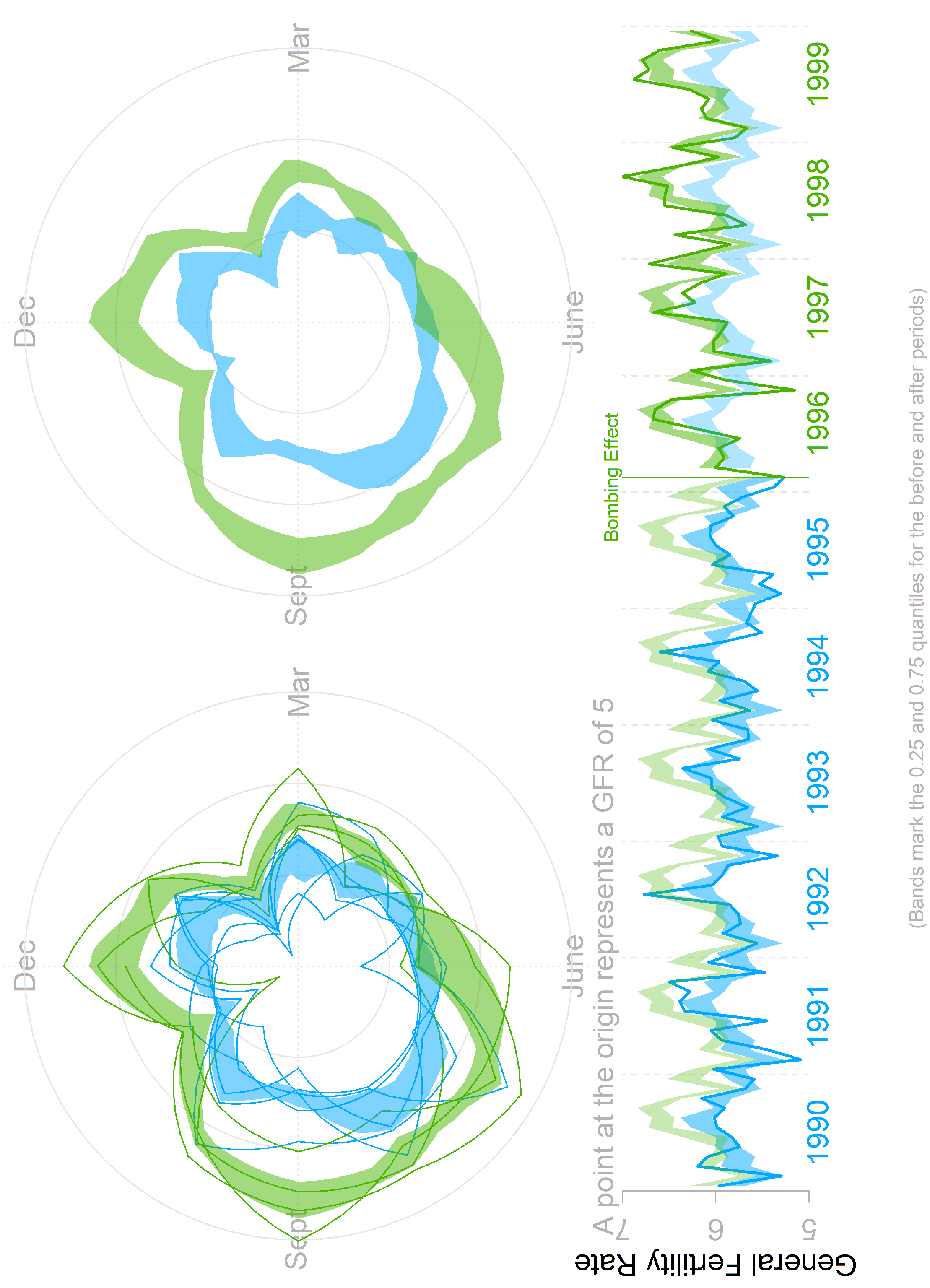


Figure 6: Wrap Around Time Series (WATS Plot) of the Oklahoma City GFR data, 1990-1999

Figure 7: WATS Plot with H-spread bands (top left), with data lines deleted (top right), and the original linear plot (bottom)



*The H-spread bands within the WATS plots are defined as they were in the linear plots, as H-spreads computed across years and within specific months, separately before and after the bombing interruption in February, 2006. The online code includes a smoothing procedure that enhances the appearance of both the raw data and the H-spread bands (note, for example, that the lines connecting the raw data are slightly curved, reflecting this smoothing process; similarly, the H-spread bands transition smoothly from one to the next). This smoothing process*

*can be easily turned on or off, or a different one can be developed, at the graph-makers’ discretion.*

*Rodgers, St. John, and Coleman (2006) also analyzed the time series associated with nine other Oklahoma counties during the 1990's. The counties analyzed were all of the counties classified as metropolitan by the U.S. Census Bureau during this period, and included five counties including and around Oklahoma City, four around Tulsa, and the county in which Lawton is located. These evaluations allowed the evaluation of three different causal explanations for the fertility effect in Oklahoma, a community-action theory, a parental insurance theory, and Terror Management Theory. The interested reader can study that paper to see these quasi-experimental comparisons, and how they were used. To provide a broader illustration of WATS plots, we present one additional Oklahoma county portrayal, styled after Figure 76 above, for ????? county; see Figure 8. This county is located near Tulsa, and like all other metropolitan counties in Oklahoma, showed little or no detectable (or visually apparent) effect of the bombing.*

*One More WATS Plot, for Illustration*

*We present one additional WATS plot example, to further illustrate several features of WATS plots. Especially, this example is for a time cycle that is different from a week, month, or year; we present campaign finance information for a House of Representative candidate over a number of two-year campaign/election cycles. [more description here] Figure 9 presents the information within this WATS plot, along with a linear plot, similar to the presentations in Figure 7 and 8.*

Conclusion

WATS Plots can be used for data portrayal, and clearly can be used to contribute substantive insight. It is striking, for example, to compare Figure 1 and the top right figure in Figure 7. These two figures are based on identical data. *Visual inspection of the graph in Figure 1* is hampered by the background variability in the birth data, so that it is difficult to easily detect the increase in births that occurred in Oklahoma County following the bombing. Once graphical

and statistical models are imposed, however, the effect is not only detectable, it is striking.

WATS Plots can be used in virtually any time series setting that extends through several periods. Besides yearly birth patterns, examples include caffeine intake *across ten days* around a 24-hour circle, or a *football team’s fall scoring record over a coach’s ten-year career.* For most time series representations, we recommend the use of *both* linear and WATS time series plots, because the two graphical methods have separate and complementary advantages. The idea of the WATS Plot is simple, but when combined with H-spread (and other confidence) bands and color level-indicators, WATS Plots serve as a powerful system of data presentation for time series researchers. Defining graphical presentation separately for group difference, especially within the context of an interrupted time series design, is facilitated by WATS Plots.

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Footnotes [DELETE this footnote]

1  The third author has developed a software system to represent rose diagrams. The Java implementation of the system is called jRose, and the R implementation is called RRose. The software and instructions can be obtained from the website <http://endaemon.com/rose>. The program will take time series data as input, and produce a standard rose diagram in color. Alternatively, in the spirit of Tufte's (2000) entreaty to optimize the data-ink ratio, the system will also produce so-called "Tufterized rose diagrams" by eliminating most of the ink and retaining the arcs that describe the values of the outcome, and the angles of the explanatory variables.