EXAMINING THE MENTAL HEALTH AND TEMPERATURE RELATIONSHIP IN NORTH CAROLINA

A Thesis
by
TYLER J. MINOR

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Abstract

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Adverse mental health outcomes have been associated with high temperatures in studies around the world. Despite the breadth of research there are few studies that explore a broad range of mental health outcomes and, to our knowledge, none specific to North Carolina, USA. This study uses a distributed lag non-linear model (DLNM) to explore the relationship between ambient temperature and mental health outcomes (suicide, self-harm and suicide ideation, anxiety and stress, mood disorders and depression) in North Carolina. The results were predominately insignificant with some key exceptions. The county with the highest climate variability (Wake) displays high levels of significance while counties with the lowest climate variability (New Hanover and Pitt) are almost entirely insignificant. This finding coincides with other studies that observe a weaker temperature-mental health relationship in geographies with low seasonal variability and for populations more adapted to the heat.

Additionally, the temperature-mental health relationship changes with respect to various outcomes and lag periods. Self-harm and suicidal ideation peaks in the warm period (June - August) and displays an increase in risk at shorter lag periods (0-5 days). Anxiety, depression, and major depressive disorders peak in the cooler months (May and September) while the highest risk is observed at longer lag periods (15-20 days). Suicide is the only outcome that favored a 20-day lag period in the sensitivity analysis. These observations suggest that there are a number of unexplored pathological and environmental variables affecting the temperature-mental health relationship.

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Table of Contents

List of Tables

List of Figures

Foreword

The findings of this thesis will be submitted to the International Journal of *Biometeorology,* an international peer-reviewed journal dedicated to the 'research and practical aspects such as living conditions, health and disease.' The format of this thesis has been adjusted accordingly.

Chapter 1

Suicide is the 10th leading cause of death in the United States (CDC 2018) and accounted for 1,499 deaths in North Carolina in 2018 (NCIOM 2020). Additionally, the national rate of suicide has increased by more than 30% in the last two decades (Stone et al. 2018). The causal reasons for suicide is complex and it's well understood that suicide is rarely cause by any single factor (Sher 2004). Evidence suggests that cumulative factors increase total risk, underlining the need to comprehensively research the various upstream components including individual circumstance, social, and environmental risk factors. A better understanding of how environmental factors affect the risk of suicidal behaviors is needed to develop effective intervention programs, especially within the context of climate change and a cascading suicide public health crises.

The mental health consequences of climate change range from minimal effects on everyday life to clinical disorders such as anxiety, depression, post-traumatic stress, and suicidality (Dodgen et al. 2016). The global consensus on climate change warns of a likely increase in global temperature by 1.5 °C and estimates that between 20-40% of the global human population live in regions that have already experienced a 1.5 °C warming relative to pre-industrial temperatures (Hoegh-Guldberg et al. 2018). Early research into climate-suicide relationships produced mixed results, often due to the misuse of climate data and poorly constructed methods (Dixon and Kalkstein 2009). Novel methods developed from geographers and climatologists better address the complexity of the problem through the use of spatial and multivariate analysis (Dixon and Kalkstein 2009). Recent temperature-suicide research employs methods that take lag-time and cumulative effects of exposure into account. Evidence in current literature shows a significant association between temperature and poor health outcomes (WHO 2003). Exposure to extreme heat is positively correlated to increased rates of suicide in adults, elderly populations, and people with pre-existing health conditions (Dodgen et al. 2016). Seasonal, demographic, and geographic variability persists, suggesting a variety of interactions that are not yet understood. Despite the complexity of compounding variables, identifying trends and mechanisms will provide insight into mitigation and adaptation strategies.

All theoretical frameworks describing the psychological path from suicidal ideation to a suicide attempt (i.e., ideation-to-action frameworks) include chronic feelings of pain and hopelessness as ubiquitous motivators (Klonsky et al. 2018). In addition, acute life events such as loss, adverse childhood experiences, and health problems are considered individual risk factors for suicide (CDC 2018). These high-stress traumas are associated with suicidal behaviors (Liu and Miller 2014) and are "central to all major theories of suicide" (O'Conner and Nock 2014). However, studying the relationship between high-stress traumas and related mental health outcomes is difficult due to uncertainty in the types of stressors that constitute acute life events and the lag time between traumas and ideation (Stewart et al. 2019). This is further complicated as each individual experiences and copes with stressful events uniquely. Understanding the psychological mechanisms that impact the risk of suicidal ideation on the individual level can help contextualize the findings of research on larger social and environmental scales.

The experience of loss, whether it be of a relationship, loved one, employment, or health status, is strongly linked to suicide and poor mental health (Krysinksa 2003). The death of a loved one is a significant predictor of suicide risk (Stewart et al. 2019), and those who are left behind struggle with grief, loss, loneliness, and existential questions about the meaning of life (Krysinska 2003). While loss under any circumstances is difficult to cope with, loss by suicide introduces unique circumstances. "Survivors" of suicide (i.e., relatives and friends of suicide victims) become victims themselves (Krysinksa 2003). They are left to deal with the negative feelings of loss and, often, perceived responsibility for causing ideation or failing to intervene (Shneidman 2001). In turn, adult survivors are more likely to experience suicidal ideation, create specific plans, and attempt suicide themselves (Crosby and Sacks 2002). Cleiren and Diekstra (1995) and Clark and Goldney (2000) describe the associated psychological mechanisms; identification with the deceased, punishment for perceived self-blame, social modeling, and belief in a family curse. Furthermore, the resulting fallout of a single suicide can balloon into a suicide cluster (i.e., a group of suicide attempts that occur closer in time and space than would be expected in a given community) (O'Carroll et al. 1988).

The number of adverse childhood exposures (ACE), such as emotional, physical, or sexual abuse and household dysfunction, has a significant effect on suicidal risk behaviors (Felitti et al. 1998). ACEs were similarly associated with mental health concerns including alcoholism, depression, and drug use (Dube et al. 2001; Cluver et al. 2015). Exposure to ACE increases the risk of attempting suicide at least once by 2-5 times (Dube et al. 2001). Additionally, cumulative ACE events further increase the likelihood of suicidal behavior (Cluver et al. 2015). Research into the impact of ACEs on mental health highlights the importance of understanding both cumulative effects and lag times within ideation-to-action frameworks.

The pathway and timeline from suicidal ideation to suicidal action is not well understood. Preliminary research by Millner et al. (2017) describes a simple sequence of ideation, deciding/planning, and attempting characterized by a relatively long period between ideation and deciding (1-5 years) followed by a relatively short period between deciding and attempting (1 week-12 hours). The short period of time between deciding and attempting suicide underscores the importance of recognizing triggers and limiting access to lethal means. Access to lethal means significantly increases the risk of suicide (Barber and Miller 2014). Reducing access to means such as firearms, charcoal, and tall buildings reduces death by suicide (Pirkis et al. 2013; Reisch et al. 2013; Yip et al. 2018). There is evidence that the risk of suicide in persons with access to means has a different relationship between females and males. Females and males employed in occupations with access to means showed suicide rates of 3.02 and 1.24 times greater than those employed in occupations without means, respectively (Milner et al. 2017).

As suggested by Durkheim's (1951) framework, suicide and mental health risks are strongly associated with poverty, economic inequality, and sharp economic turns (McDaid and Kennelly 2009). Economic crises and unemployment generally correlate with rising rates of suicide (Chang et al. 2009; Milner et al. 2014). Poverty is a significant social predictor for poor mental health and suicide with almost 75% of total suicides occurring in low- and middle-income countries (Bantjes et al. 2016). During the 2008-2009 recession county-level poverty, foreclosures, and unemployment were significantly associated with alcohol-related suicides in the United States (Phillips and Nugent 2014; Kerr et al. 2017). County-level poverty similarly correlates with rates of pediatric suicide (Hoffmann et al. 2020). Durkheim (1951) suggests that these sharp economic turns outpace the rate at which social norms can change, creating a society that is no longer capable of meeting the needs of the people. Conversely, strong social cohesion in Spain and Portugal and social welfare programs in Nordic countries have been seen to reduce the impact of economic collapse on rates of suicide (Wahlbeck and McDaid 2012). These social safety nets effectively act as a buffer that allow social norms to catch up with rapidly changing economic conditions.

Research Gaps

The current state of the literature establishes consensus on only a few components of the temperature-suicide association; a significant correlation between temperature and suicide, the existence of a peak in the warm season, and the relative vulnerability of elderly populations (Kim et al. 2011; Dixon and Kalkstein 2018). Climatic, demographic, and geographic variances are complexly interwoven, shrouding much of our understanding in ambiguity. This is particularly evident in our lack of understanding with regards to the psychological mechanisms that link temperature and mental health. A fundamental understanding of changes at the biologic level could help identify the key environmental factors that affect mental health. In lieu of such advances the diversification of research contexts is needed to uncouple the complex effects of environmental risk factors. Most mental health research is focused on adult and elderly populations in mid and upper-income countries. Varying target populations, scales, and geographies provide insight that could eventually coalesce into broader consensus. Additionally, novel data streams, methods, and temperature metrics could reveal completely new relationships.

EXAMINING THE MENTAL HEALTH AND TEMPERATURE RELATIONSHIP IN NORTH CAROLINA

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Abstract

Adverse mental health outcomes have been associated with high temperatures in studies around the world. Despite the breadth of research there are few studies that explore a broad range of mental health outcomes and, to our knowledge, none specific to North Carolina, USA. This study uses a distributed lag non-linear model (DLNM) to explore the relationship between ambient temperature and mental health outcomes (suicide, self-harm and suicide ideation, anxiety and stress, mood disorders and depression) in North Carolina. The results were predominately insignificant with some key exceptions. The county with the highest climate variability (Wake) displays high levels of significance while counties with the lowest climate variability (New Hanover and Pitt) are almost entirely insignificant. This finding coincides with other studies that observe a weaker temperature-mental health relationship in geographies with low seasonal variability and for populations more adapted to the heat. Additionally, the temperature-mental health relationship changes with respect to various outcomes and lag periods. Self-harm and suicidal ideation peaks in the warm period (June - August) and displays an increase in risk at shorter lag periods (0-5 days). Anxiety, depression, and major depressive disorders peak in the cooler months (May and September) while the highest risk is observed at longer lag periods (15-20 days). Suicide is the only outcome that favored a 20-day lag period in the sensitivity analysis. These observations suggest that there are a number of unexplored pathological and environmental variables affecting the temperature-mental health relationship.

Background

Mental illness impacts more than 50% of people during their lifetime, and in any given year 1 in 5 people in the United States will experience mental illness (CDC 2018). Mental illness incorporates a variety of experiences ranging from temporary changes in mood and behavior to chronic disorders including paranoia, depression, anxiety, bipolar disorder, post-traumatic stress disorder, and suicidal ideation (CDC 2018). Untreated and undiagnosed mental illnesses are widely seen as the most significant predictors of suicide, but the factors affecting the risk of suicide rarely act alone (CDC 2018). A variety of individual, social, and environmental factors have been linked to increased mental health issues and suicide rates. However, assessing the environmental risk factors of poor mental health outcomes is challenging due to the social stigmas surrounding mental health, reliance on self-reporting, clinicians often failing to recognize the role of the physical environment, and understanding the psychological mechanisms that lead to mental health decline (Bolton et al. 2015). Thus, innovations in data collection, analytical methods, and research integration are needed to understand the various, interrelated impacts of the risk factors of mental health.

Increased temperatures are positively correlated with increased rates of poor mental health outcomes ranging from increased feelings of anxiety and depression to suicidal ideation and attempts. Noelke et al. (2016) shows that negative impacts to relative well-being can start at temperatures as low as 70 °F (21 °C) with significant increases in negative emotions, stress, and fatigue at temperatures above 90 °F (32 °C). Feelings of depression are amplified at high temperatures (Qi et al. 2009). Additionally, impulsivity and aggression are suggested to increase above certain temperature thresholds, increasing the risk of suicide (Page et al. 2007; Page and Howard 2010; Basu et al. 2017). Increased aggression is further supported by increased crime and homicide rates in warmer weather (Butke and Sheridan 2010; Anderson 2011) as well as a stronger association between temperature and violent suicide methods (Dodgen et al. 2016). These findings are consistent across geographic boundaries as numerous countries including the United States, Australia, China, Canada, and Taiwan have identified positive correlations between increased temperatures and increased emergency room visits and hospitalizations for mental health crises (Kaiser et al. 2001; Khalaj et al. 2010; Vida et al. 2012; Wang et al. 2014; Peng et al. 2017; Basu et al. 2017). Studies have similarly identified temperature-suicide relationships across mid-latitude and sub-tropical climates (Dixon et al. 2007; Dixon and Kalkstein 2018). There are nuances of the temperature-suicide relationship that are still poorly understood involving seasonality, disparities between affected populations, and geographic variability.

Many temperature-suicide studies identify a period in the late spring in which suicides spike but there is little consensus on the environmental thresholds that preempt the spike (Dixon and Kalkstein 2018). There is some evidence that climatic variables may not be directly linked to the spring spike as countries that are more industrialized experience lower peaks (Chew and McCleary 1995). The diminished peak may be due to industrialized regions being uncoupled from seasonal cycles relative to agricultural regions (Chew and McCleary 1995). This finding is further supported by decreasing suicide seasonality and increasing industrialization in Finland since the 1920's (Näyhä 1982). Durkheim dismissed environmental factors as the cause of the spring spike, instead proposing that 'voluntary deaths increase from January to July because social life is more intense.' This evidence and Durkheim's (1951) proposal is indicative of a theory in which climatic variables are simply proxies for the disruption of social and economic systems. Dixon and Kalkstein (2009) argue that, despite uncertainty surrounding specific mechanisms, continued research into climate-suicide relationships is important because the 'identification of links between environmental conditions and behavioral responses are able to be mitigated or intervened upon even if causes are poorly understood.'

The impact of extreme temperature on mental health notably varies across different demographics. There are increased suicide rates in warmer seasons and stronger relationships in men and elderly populations than women and young people, respectively (Preti and Miotto 1998; Kim et al. 2011; Kim et al. 2016). Additionally, Bouchama et al. (2007) found that individuals with mental health conditions were up to three times more likely to die when exposed to extreme heat events. There is no literature consensus on the mechanisms behind these demographic disparities. Prevailing theories suggest that medications affecting temperature regulation, social isolation, and limited time outdoors could significantly contribute (Dodgen et al. 2016).

The magnitude and character of temperature-suicide correlation varies across geographies. In a multi-centre study Kim et al. (2019) identified significant non-linear variance in temperature-suicide associations, signifying that there are complex mediating variables present that are not yet understood. Evidence shows that cities with high climate variability may experience a higher temperature-suicide relationship (Dixon and Kalkstein 2018; Sugg et al. 2019). Historically, rural areas around the world have greater rates of suicide (Dudley et al. 1998; Ji et al. 2001) but recent studies link urban areas to increased rates of poor mental health (Tost et al. 2015). The effects of urban heat islands are particularly relevant as they have been linked to increased rates of suicide in elderly populations in Taipei (Chern et al. 2016). Other seasonal variables such as exposure to sunlight, vitamin D levels, outdoor activity, and diet have been proposed as additional risk factors (Kim et al. 2019).

The relationship between extreme temperature and mental health is not well defined and has yet to be studied across a broad range of mental health outcomes (e.g., self-harm, suicide, depression, etc.). While there have been a number of studies detailing the connections in the US, Asia, and Australia there is still much to be understood and to the author's knowledge no study has examined the relationship in North Carolina, USA. The aim of this study is to determine if an association exists between mental health outcomes (i.e., suicide, self-harm and suicide ideation, anxiety and stress, mood disorders and depression) and temperature in North Carolina using emergency department visits from 2016 to 2018 and suicide fatalities from 2006 to 2018. More specifically, this study will address the following research questions: 1) Is there an association between suicide, mental health, and temperature? 2) How does this relationship vary across different geographic counties in NC? Results from our study will provide new understanding on the complexity of mental health outcomes and temperature for a US state located in a subtropical climate. This is of particular importance as North Carolina is experiencing rising temperatures (Frankson et al. 2022).

Methods

Study area

For this analysis, we focused on Buncombe, Mecklenburg, Guilford, Wake, Pitt, and New Hanover counties. These study areas were selected because they represent a range of climates across North Carolina while supporting a large enough sample size for the statistical analysis.

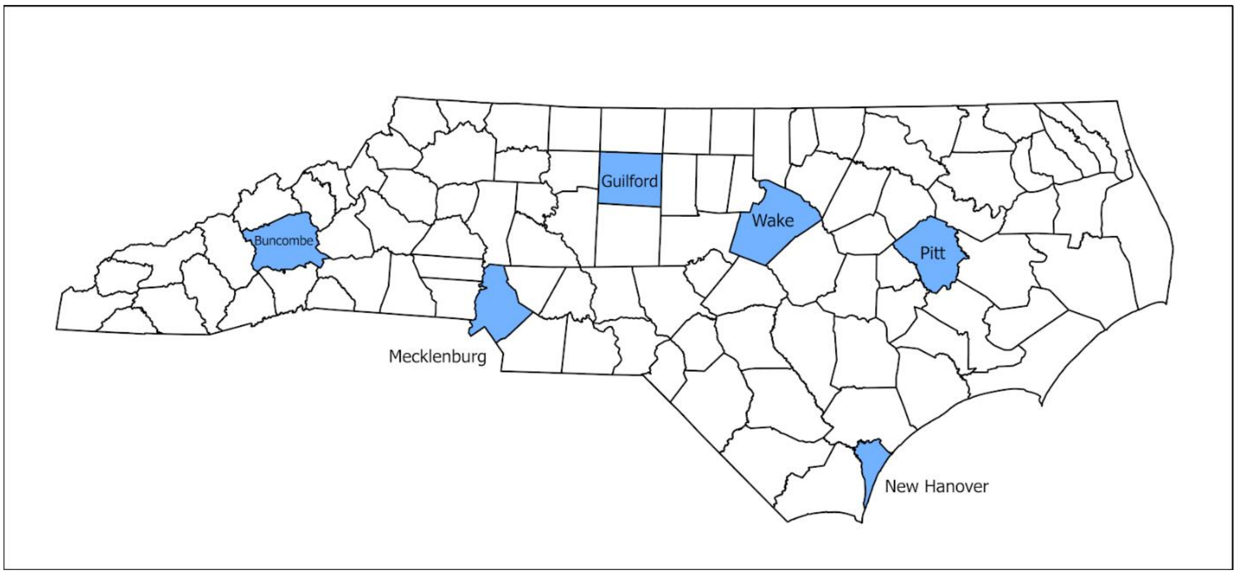

Fig. 1. Map of North Carolina counties included in study area.

Mental Health Outcomes

This ecological study included North Carolina residents who died by suicide and visited the emergency department (ED) for depression or suicide ideation/self-harm from 2016 to 2018. ED data were provided by the North Carolina Disease Event Tracking and Epidemiologic Collection Tool (NC-DETECT), which offers statewide surveillance for 117 emergency departments (99%) in the state of NC (Ising et al. 2011). Completed suicides were identified from the North Carolina Violent Death Reporting System (NC-VDRS) from 2006 to 2018, and geolocations were determined using death certificate data which included residential addresses of the deceased. ED visits were flagged using ICD-9/ICD-10 injury codes as: 'suicide attempt, suicidal ideation, self-harm or poisoning' (ICD9: E950 - E959; ICD-10: T36-T65, X60-X84, R45.841, T7, T14.91), or 'depressive disorders' using ICD-9/ICD-10 diagnosis codes (ICD9:311; ICD10: F329).

Temperature Exposure Assessment

Daily average temperature was obtained from NOAA National Centers for Environmental Information nClimGrid, a spatially resolved dataset at the county level (Vose et al. 2014). A daily time series consisting of daily county-level temperature and ED-related visits for mental health or completed suicides was constructed.

Statistical Analysis

Mapping and analyses were conducted at the county level, the smallest spatial scale available for both data sets. Descriptive statistics were computed for each data set and significance was reported at p-value < 0.05. Health outcomes are often delayed and non-linear in response to temperature exposure (Guo et al. 2011; Wang et al. 2014). A quasi-Poisson generalized linear model and a distributed lag non-linear model (DLNM) was applied to estimate relationships between temperature and mental health outcomes (e.g., Dixon et al. 2007; Dixon & Kalkstein 2018; Sugg et al. 2019). The "dlnm" package in R modeled the exposure-lag-response associations by using cross-basis matrices to account for the cumulative effects of temperature exposure (Gasparrini 2011). The presence and influence of seasonality were addressed with the forecast package in R by compiling models for the annual (2016 - 2018) and seasonal scales using equally spaced spline knots at 3 and 5 for NC-DETECT data and 13 and 11 for VDRS data (e.g., Hyndman and Khandakar 2008; Sugg et al. 2019). ED outcomes were explored during the warm season, defined as May through May through September (e.g., Dixon and Kalkstein 2018; Sugg et al. 2019). Due to constraints within the sample size, suicide outcomes were explored for the entire year. Weekly patterns were accounted for with an "day of week" indicator variable. Three-dimensional plots were constructed to summarize lag-exposure-response relationships between the relative risk (RR) of poor mental health outcomes and temperature.

Sensitivity analysis

A sensitivity analysis that varies the degrees of freedom for the lag polynomial, temperature spline, and lag time were used to test the robustness of the models (e.g., Ma et al. 2015; Dixon & Kalkstein 2018; Sugg et al. 2019). A modification of the quasi-Akaike Information Criterion (qAIC) is common in the literature (e.g., Gasparrini et al. 2010; Guo et al. 2011; Rocklov et al. 2012; Gao et al. 2015; Guo et al. 2017; Sugg et al. 2019). The models displayed are selected based on the qAIC value after considering several models. Within the crossbases degrees of freedom for the lag polynomial (3-8), temperature spline (2-4), and maximum lag time (0, 6, 13, 20) were varied. Additionally, stratification, day of week, and temperature spline variables were explored within the linear models. The inclusion of the stratification variable displayed the greatest impact on qAIC values, increasing the qAIC value by 20-25% across all variables. Despite some marginal increases in qAIC values the day of week and temperature spline variables were included in the model due to their almost ubiquitous presences in the literature. Final models are non-stratified and include the day of week, temperature spline, a lag polynomial of 3, a temperature spline of 2. The impact of the maximum lag period had a relatively small impact on the qAIC (5-10%) but displayed consistent trends (Supplementary Table 1). All emergency room models favored a 0-day lag period while all suicide models favored a 20-day lag period. Similar to Peng et al. (2017), we included results for all lag periods to explore the impact of cumulative exposure on the temperature-mental health relationship.

Results

Emergency Room and Temperature Characteristics

Table 1 summarizes the cumulative monthly count of suicide-related ED visits during the study period for each of the explored counties. Almost 150,000 emergency room visits flagged as suicide attempt, suicidal ideation, self-harm or poisoning, mood, anxiety, and major depressive disorders were reported within the study period (*n* = 28,586 in Buncombe, *n* = 36,451 in Guilford, *n* = 33,721 in Mecklenburg, *n* = 18,913 in New Hanover, *n* = 11,456 in Pitt, and *n* = 19,796 in Wake). Mood disorders were the most commonly reported visits (*n* =57,328) while self harm and suicide ideation visits were the least common (n =13,632). Anxiety and depressive disorder visits had 41,388 and 36,625 reports, respectively. A total of 2,617 suicides were reported (Table 1) .

Buncombe

	Anxiety Disorders	Major Depressive Disorders	Mood Disorders	Self Harm and Ideation	Average (°C) Temperature
May	2093 (23.2%)	1523 (22.0%)	2671 (22.2%)	91 (15.7%)	17.22
June	1659 (18.4%)	1350 (19.5%)	2286 (19.0%)	109 (18.8%)	20.97
July	1623 (18.0%)	1231 (17.8%)	2151 (17.8%)	132 (22.8%)	22.65
August	1692 (18.8%)	1281 (18.5%)	2255 (18.7%)	139 (24.0%)	21.74
September	1950 (21.6%)	1547 (22.3%)	2695 (22.4%)	108 (18.7%)	19.94

Guilford

	Anxiety Disorders	Major Depressive Disorders	Mood Disorders	Self Harm and Ideation	Average (°C) Temperature
May	2230 (22.4%)	2290 (23.5%)	3408 (23.4%)	408 (18.3%)	19.93
June	1699 (17.1%)	1912 (19.6%)	2863 (19.7%)	440 (19.7%)	23.98
July	1788 (18.0%)	1827 (18.8%)	2720 (18.7%)	472 (21.1%)	26.11
August	1951 (19.6%)	1738 (17.8%)	2594 (17.8%)	445 (19.9%)	25.23
September	2267 (22.8%)	1973 (20.3%)	2957 (20.3%)	469 (21.0%)	22.77

New Hanover

	Anxiety Disorders	Major Depressive Disorders	Mood Disorders	Self Harm and Ideation	Average (°C) Temperature
May	913 (15.8%)	891 (17.3%)	1238 (17.5%)	147 (15.8%)	22.27
June	923 (16.0%)	778 (15.1%)	1165 (16.5%)	167 (17.9%)	25.90
July	1225 (21.2%)	1014 (19.7%)	1445 (20.4%)	235 (25.2%)	27.35
August	1365 (23.6%)	1242 (24.2%)	1635 (23.1%)	173 (18.6%)	26.99
September	1350 (23.4%)	1213 (23.6%)	1584 (22.4%)	210 (22.5%)	25.06

Mecklenburg

	Anxiety Disorders	Major Depressive Disorders	Mood Disorders	Self Harm and Ideation	Average (°C) Temperature
May	1923 (21.9%)	1829 (22.9%)	2855 (22.5%)	905 (21.3%)	20.95
June	1768 (20.1%)	1577 (19.8%)	2566 (20.2%)	899 (21.1%)	25.06
July	1616 (18.4%)	1524 (19.1%)	2418 (19.0%)	905 (21.3%)	26.94
August	1617 (18.4%)	1368 (17.1%)	2198 (17.3%)	800 (18.8%)	26.14
September	1856 (21.1%)	1686 (21.1%)	2669 (21.0%)	742 (17.5%)	23.97

Pitt

	Anxiety Disorders	Major Depressive Disorders	Mood Disorders	Self Harm and Ideation	Average (°C) Temperature
May	525 (18.3%)	542 (18.1%)	867 (18.4%)	167 (19.0%)	21.29
June	528 (18.4%)	563 (18.8%)	860 (18.2%)	199 (22.6%)	25.03
July	592 (20.7%)	563 (18.8%)	944 (20.0%)	173 (19.7%)	26.87
August	633 (22.1%)	675 (22.6%)	1060 (22.5%)	176 (20.0%)	26.35
September	586 (20.5%)	650 (21.7%)	988 (20.9%)	165 (18.8%)	24.29

Wake

	Anxiety Disorders	Major Depressive Disorders	Mood Disorders	Self Harm and Ideation	Average (°C) Temperature
May	942 (19.0%)	807 (21.0%)	1275 (20.4%)	939 (19.7%)	20.78
June	786 (15.8%)	603 (15.7%)	986 (15.8%)	978 (20.6%)	24.60
July	962 (19.4%)	687 (17.9%)	1136 (18.2%)	981 (20.6%)	26.83
August	1064 (21.4%)	798 (20.8%)	1285 (20.6%)	942 (19.8%)	26.04
September	1212 (24.4%)	943 (24.6%)	1554 (24.9%)	916 (19.3%)	23.56

Table 1. Cumulative ED visits in each county.

Table 2 displays temperature thresholds (Minimum, 25th, 50th, 75th, Maximum, and Interquartile Range) for each county. New Hanover, the most coastal county in the study area, had the lowest temperature range with an IQR of 3.09 and the highest temperatures across all quantiles. Guilford, located in the mountain region of NC, had the second lowest IQR (3.40) and the lowest temperatures across all quantiles. The most centrally located county, Wake, had the highest IQR (4.01). This distribution of ambient temperatures across the study counties is consistent with expectations based on the regional climates of North Carolina.

Temp (°C)	Buncombe	Guilford	Mecklenburg	New Hanover	Pitt	Wake
Min	6.94	10.61	12.52	14.82	13.72	12.73
25th	19.27	22.11	23.06	24.35	23.43	22.76
50th	21.06	24.36	25.26	26.04	25.41	24.91
75th	22.68	25.95	26.98	27.44	26.98	26.76
Max	25.45	29.74	30.05	30.92	30.17	29.82
IQR	3.40	3.84	3.91	3.09	3.54	4.01
Range	18.51	19.13	17.53	16.10	16.45	17.09

Table 2. Summary of temperature distributions across the study period for each county.

Delay in mental health response following temperature exposure

Table 3 shows the calculated relative risk (RR) and 95% confidence interval for the lagged response times for emergency room visits and suicides at different lag periods in each of the counties included in the study area. Values highlighted in red notate a statistically significant increase in RR while values highlighted in blue notate a statistically significant decrease in RR.

Buncombe

		Lag 0	Lag 6	Lag 13	Lag 20
Anxiety Disorder	**1st**	0.924(0.75-1.139)	1.019(0.691-1.502)	1.188(0.669-2.108)	0.74(0.316-1.729)
	25th	0.988(0.926-1.054)	1.06(0.934-1.203)	1.258(1.024-1.546)	1.921(1.392-2.652)
	50th	1(0.998-1.002)	1.002(0.998-1.006)	1.007(1.001-1.013)	1.021(1.011-1.031)
	75th	0.995(0.93-1.063)	0.919(0.816-1.036)	0.892(0.754-1.054)	0.753(0.594-0.954)
	99th	0.965(0.761-1.224)	0.826(0.532-1.284)	1.005(0.529-1.912)	1.258(0.531-2.977)
Major Depressive Disorder	**1st**	0.908(0.73-1.129)	0.883(0.585-1.333)	0.855(0.467-1.567)	0.629(0.259-1.526)
	25th	1.016(0.952-1.085)	1.045(0.919-1.188)	1.276(1.036-1.571)	1.556(1.118-2.166)
	50th	1.001(0.999-1.002)	1.002(0.998-1.006)	1.007(1.001-1.014)	1.014(1.003-1.024)
	75th	1.007(0.943-1.075)	0.955(0.847-1.076)	0.94(0.794-1.113)	0.903(0.709-1.15)
	99th	1.064(0.844-1.34)	0.93(0.599-1.445)	1.277(0.674-2.421)	1.64(0.691-3.896)
Mood Disorder	**1st**	0.912(0.756-1.1)	0.853(0.598-1.216)	1.034(0.614-1.741)	0.758(0.352-1.629)
	25th	1.006(0.951-1.065)	1.022(0.914-1.143)	1.144(0.955-1.371)	1.54(1.157-2.051)
	50th	1(0.999-1.002)	1.001(0.998-1.005)	1.005(0.999-1.01)	1.014(1.005-1.023)
	75th	0.984(0.929-1.042)	0.912(0.823-1.012)	0.887(0.766-1.027)	0.835(0.678-1.028)
	99th	0.962(0.786-1.179)	0.762(0.52-1.116)	0.837(0.48-1.459)	1.2(0.57-2.523)
Self Harm and Ideation	**1st**	0.352(0.174-0.713)	0.105(0.028-0.398)	0.095(0.017-0.538)	0.052(0.004-0.597)
	25th	0.837(0.704-0.996)	0.916(0.663-1.267)	0.967(0.575-1.627)	0.777(0.34-1.779)
	50th	0.995(0.99-1.001)	1(0.99-1.01)	1.002(0.986-1.018)	0.997(0.972-1.023)
	75th	1.085(0.932-1.263)	0.972(0.743-1.27)	0.948(0.641-1.402)	0.835(0.476-1.468)
	99th	1.044(0.627-1.739)	0.92(0.363-2.332)	0.938(0.228-3.853)	0.42(0.061-2.911)
Suicide	**1st**	1.291(0.684-2.436)	1.721(0.577-5.128)	1.388(0.251-7.683)	0.485(0.042-5.562)
	25th	0.994(0.74-1.334)	0.787(0.472-1.314)	1.042(0.483-2.249)	1.339(0.447-4.013)
	50th	1.007(0.985-1.03)	1.024(0.985-1.064)	0.996(0.941-1.056)	0.968(0.892-1.05)
	75th	1.229(0.923-1.635)	1.126(0.697-1.82)	0.863(0.426-1.746)	0.739(0.274-1.993)
	99th	1.67(0.807-3.455)	0.857(0.253-2.906)	0.652(0.111-3.816)	0.785(0.064-9.67)

		Guilford			
		Lag 0	**Lag 6**	**Lag 13**	**Lag 20**
Anxiety Disorder	**1st**	0.861(0.732-1.013)	0.728(0.561-0.944)	0.769(0.516-1.146)	0.635(0.341-1.185)
	25th	1.001(0.946-1.06)	1.041(0.932-1.164)	1.106(0.919-1.33)	1.088(0.8-1.479)
	50th	1.002(0.993-1.011)	1.01(0.993-1.028)	1.021(0.991-1.051)	1.016(0.968-1.066)
	75th	0.98(0.948-1.013)	0.941(0.886-1)	0.901(0.817-0.994)	0.968(0.836-1.122)
	99th	0.909(0.769-1.074)	0.814(0.613-1.082)	0.736(0.455-1.19)	1.104(0.558-2.185)
Major Depressive Disorder	**1st**	0.988(0.842-1.159)	1.069(0.84-1.361)	1.547(1.085-2.207)	1.652(0.997-2.739)
	25th	0.996(0.942-1.053)	1.005(0.903-1.119)	1.241(1.035-1.487)	1.414(1.045-1.912)
	50th	0.999(0.99-1.008)	1.002(0.985-1.019)	1.031(1.003-1.061)	1.045(0.997-1.095)
	75th	1.007(0.973-1.041)	0.974(0.917-1.035)	0.943(0.856-1.039)	1.024(0.885-1.185)
	99th	1.03(0.866-1.224)	0.863(0.638-1.166)	1.209(0.734-1.991)	2.784(1.35-5.738)
Mood Disorder	**1st**	0.961(0.831-1.112)	1.019(0.815-1.272)	1.373(0.988-1.909)	1.514(0.945-2.425)
	25th	0.999(0.95-1.051)	0.982(0.891-1.081)	1.14(0.969-1.341)	1.216(0.928-1.594)
	50th	1(0.992-1.008)	0.998(0.983-1.014)	1.02(0.994-1.046)	1.026(0.983-1.07)
	75th	1.006(0.975-1.037)	0.982(0.93-1.036)	0.947(0.87-1.032)	0.997(0.876-1.135)
	99th	1.038(0.888-1.214)	0.849(0.645-1.118)	1(0.637-1.57)	1.59(0.835-3.026)
Self Harm and Ideation	**1st**	0.97(0.694-1.357)	1.199(0.722-1.991)	1.525(0.717-3.243)	2.297(0.785-6.722)
	25th	1.051(0.959-1.153)	1.033(0.866-1.233)	1.296(0.963-1.745)	1.744(1.089-2.794)
	50th	1.009(0.994-1.024)	1.004(0.977-1.033)	1.037(0.99-1.087)	1.088(1.01-1.171)
	75th	0.964(0.913-1.017)	0.988(0.901-1.084)	0.95(0.822-1.097)	0.811(0.653-1.008)
	99th	0.927(0.699-1.228)	0.997(0.609-1.634)	1.423(0.641-3.156)	1.205(0.415-3.502)
Suicide	**1st**	0.947(0.543-1.652)	1.512(0.626-3.654)	2.096(0.553-7.953)	1.188(0.176-7.998)
	25th	1.131(0.861-1.487)	1.253(0.787-1.993)	1.123(0.564-2.235)	0.573(0.218-1.508)
	50th	0.999(0.996-1.002)	0.999(0.994-1.004)	1.001(0.994-1.008)	1.007(0.997-1.018)
	75th	0.955(0.729-1.249)	1.21(0.783-1.87)	1.433(0.759-2.704)	1.507(0.61-3.727)
	99th	1.134(0.578-2.227)	2.398(0.803-7.159)	2.851(0.555-14.637)	1.076(0.1-11.607)

		Mecklenburg			
		Lag 0	**Lag 6**	**Lag 13**	**Lag 20**
Anxiety Disorder	**1st**	0.801(0.668-0.96)	0.763(0.575-1.012)	0.743(0.485-1.138)	0.345(0.179-0.665)
	25th	0.999(0.936-1.066)	1.011(0.891-1.148)	0.942(0.764-1.16)	1.135(0.821-1.57)
	50th	1.003(0.995-1.011)	1.003(0.988-1.019)	0.995(0.97-1.021)	1.021(0.981-1.063)
	75th	0.944(0.9-0.991)	0.971(0.893-1.057)	0.993(0.873-1.129)	0.953(0.787-1.153)
	99th	0.814(0.682-0.972)	0.938(0.692-1.271)	0.895(0.551-1.452)	1.181(0.623-2.241)
Major Depressive Disorder	**1st**	0.853(0.715-1.017)	0.942(0.716-1.239)	0.926(0.611-1.402)	0.508(0.27-0.957)
	25th	1.004(0.941-1.071)	1.023(0.902-1.16)	1.154(0.938-1.419)	1.641(1.2-2.246)
	50th	1.003(0.995-1.011)	1.005(0.99-1.021)	1.018(0.993-1.045)	1.067(1.026-1.109)
	75th	0.946(0.901-0.994)	0.93(0.854-1.012)	0.945(0.831-1.075)	0.824(0.684-0.993)
	99th	0.824(0.689-0.985)	0.787(0.577-1.073)	1.06(0.653-1.72)	1.287(0.687-2.409)
Mood Disorder	**1st**	0.84(0.72-0.98)	0.904(0.711-1.149)	0.828(0.576-1.19)	0.449(0.258-0.781)
	25th	1.007(0.953-1.064)	1.034(0.928-1.152)	1.119(0.937-1.337)	1.43(1.091-1.875)
	50th	1.003(0.997-1.01)	1.007(0.994-1.021)	1.017(0.995-1.039)	1.052(1.017-1.088)
	75th	0.948(0.909-0.988)	0.914(0.85-0.983)	0.904(0.81-1.009)	0.799(0.682-0.937)
	99th	0.834(0.716-0.971)	0.754(0.577-0.985)	0.847(0.56-1.281)	0.887(0.521-1.511)
Self Harm and Ideation	**1st**	0.738(0.592-0.921)	0.651(0.458-0.926)	0.482(0.29-0.803)	0.285(0.13-0.622)
	25th	0.989(0.916-1.068)	1.151(0.993-1.335)	1.472(1.156-1.874)	1.706(1.168-2.491)
	50th	1.001(0.991-1.01)	1.019(1-1.038)	1.052(1.021-1.083)	1.071(1.022-1.123)
	75th	0.991(0.939-1.046)	0.972(0.883-1.07)	0.892(0.77-1.033)	0.9(0.722-1.122)
	99th	0.977(0.811-1.177)	1.228(0.891-1.691)	1.438(0.858-2.41)	2.094(1.043-4.204)
Suicide	**1st**	0.775(0.471-1.274)	0.823(0.362-1.871)	0.337(0.092-1.243)	0.282(0.044-1.791)
	25th	0.923(0.732-1.165)	1.098(0.738-1.634)	1.009(0.559-1.822)	1.228(0.536-2.813)
	50th	1.002(0.993-1.011)	0.995(0.98-1.009)	0.993(0.971-1.014)	0.984(0.956-1.014)
	75th	1.06(0.828-1.355)	0.877(0.585-1.314)	0.806(0.45-1.443)	0.742(0.324-1.702)
	99th	1.102(0.629-1.93)	0.867(0.347-2.164)	0.778(0.213-2.845)	0.903(0.135-6.042)

		New Hanover			
		Lag 0	**Lag 6**	**Lag 13**	**Lag 20**
Anxiety Disorder	**1st**	0.913(0.711-1.172)	0.93(0.622-1.39)	0.862(0.474-1.568)	1.003(0.403-2.499)
	25th	0.942(0.871-1.02)	1.073(0.912-1.262)	1.016(0.77-1.342)	1.189(0.737-1.916)
	50th	0.999(0.997-1.001)	1.002(0.998-1.005)	1.001(0.995-1.006)	1.004(0.995-1.014)
	75th	1.018(0.985-1.052)	0.969(0.909-1.033)	0.982(0.889-1.085)	0.915(0.78-1.072)
	99th	0.949(0.779-1.156)	0.981(0.685-1.403)	0.899(0.478-1.692)	0.793(0.289-2.18)
Major Depressive Disorder	**1st**	0.809(0.632-1.034)	0.733(0.494-1.088)	0.803(0.452-1.426)	1.232(0.509-2.985)
	25th	0.947(0.876-1.023)	1.105(0.942-1.297)	0.959(0.73-1.259)	1.284(0.799-2.063)
	50th	0.999(0.998-1.001)	1.003(0.999-1.006)	1(0.994-1.005)	1.005(0.996-1.015)
	75th	1.011(0.979-1.045)	0.941(0.884-1.002)	0.985(0.893-1.086)	0.894(0.765-1.045)
	99th	0.924(0.758-1.125)	0.845(0.587-1.215)	0.716(0.38-1.349)	0.833(0.301-2.308)
Mood Disorder	**1st**	0.864(0.682-1.094)	0.769(0.523-1.132)	0.905(0.52-1.574)	1.143(0.487-2.685)
	25th	0.946(0.878-1.02)	1.121(0.96-1.309)	1.001(0.77-1.302)	1.246(0.789-1.968)
	50th	0.999(0.998-1.001)	1.003(1-1.006)	1(0.995-1.006)	1.005(0.996-1.014)
	75th	1.01(0.979-1.042)	0.942(0.887-1.001)	0.989(0.901-1.087)	0.912(0.784-1.06)
	99th	0.895(0.739-1.084)	0.904(0.636-1.286)	0.906(0.495-1.659)	0.929(0.35-2.464)
Self Harm and Ideation	**1st**	0.644(0.352-1.178)	0.198(0.07-0.561)	0.217(0.053-0.883)	0.181(0.022-1.459)
	25th	0.994(0.853-1.158)	1.149(0.834-1.583)	1.141(0.664-1.96)	0.626(0.264-1.485)
	50th	1(0.997-1.003)	1.004(0.998-1.011)	1.004(0.993-1.015)	0.992(0.974-1.009)
	75th	1.011(0.949-1.078)	0.916(0.806-1.041)	0.933(0.764-1.14)	1.17(0.861-1.589)
	99th	1.232(0.856-1.775)	0.994(0.51-1.938)	1.179(0.372-3.741)	1.006(0.178-5.695)
Suicide	**1st**				
	25th				
	50th				
	75th				
	99th				

Pitt

		Lag 0	Lag 6	Lag 13	Lag 20
Anxiety Disorder	1st	1.025(0.746-1.408)	1.103(0.64-1.901)	1.391(0.608-3.178)	1.6(0.45-5.688)
	25th	1.015(0.924-1.116)	0.954(0.772-1.178)	1.26(0.895-1.774)	0.682(0.38-1.226)
	50th	1.001(0.984-1.019)	0.993(0.955-1.032)	1.037(0.975-1.104)	0.928(0.834-1.033)
	75th	1.016(0.961-1.073)	0.978(0.884-1.081)	0.987(0.853-1.141)	1.158(0.93-1.442)
	99th	1.153(0.849-1.565)	0.735(0.403-1.34)	1.779(0.683-4.629)	0.717(0.165-3.111)
Major Depressive Disorder	1st	1.013(0.728-1.408)	0.772(0.434-1.375)	0.795(0.334-1.893)	0.374(0.101-1.383)
	25th	1.024(0.928-1.129)	0.855(0.686-1.065)	0.968(0.676-1.385)	0.866(0.47-1.594)
	50th	1.003(0.985-1.021)	0.976(0.937-1.016)	1.004(0.94-1.071)	0.981(0.878-1.096)
	75th	1.012(0.956-1.072)	1.003(0.904-1.113)	0.874(0.752-1.015)	1.031(0.824-1.29)
	99th	1.158(0.836-1.603)	0.655(0.346-1.241)	0.397(0.144-1.093)	0.92(0.2-4.238)
Mood Disorder	1st	1.067(0.806-1.414)	0.825(0.506-1.346)	1.019(0.488-2.126)	0.799(0.262-2.437)
	25th	1.034(0.951-1.124)	0.904(0.75-1.091)	1.019(0.75-1.384)	0.689(0.409-1.162)
	50th	1.005(0.989-1.021)	0.985(0.952-1.02)	1.008(0.953-1.066)	0.937(0.852-1.03)
	75th	1.004(0.956-1.054)	0.993(0.909-1.084)	0.921(0.81-1.046)	1.103(0.91-1.337)
	99th	1.123(0.855-1.475)	0.721(0.423-1.231)	0.624(0.266-1.461)	0.611(0.168-2.228)
Self Harm and Ideation	1st	0.935(0.577-1.517)	0.427(0.182-1.003)	0.228(0.067-0.776)	0.218(0.037-1.268)
	25th	1.141(0.99-1.314)	1.237(0.903-1.696)	1.838(1.068-3.161)	0.694(0.277-1.736)
	50th	1.024(0.998-1.051)	1.046(0.987-1.108)	1.125(1.02-1.242)	0.945(0.8-1.116)
	75th	0.969(0.891-1.052)	0.931(0.8-1.084)	0.873(0.696-1.095)	1.129(0.804-1.586)
	99th	1.243(0.781-1.976)	1.423(0.576-3.512)	3.581(0.783-6.385)	0.901(0.09-9.043)
Suicide	1st				
	25th				
	50th				
	75th				
	99th				

		Wake			
		Lag 0	**Lag 6**	**Lag 13**	**Lag 20**
Anxiety Disorder	**1st**	0.886(0.68-1.152)	0.669(0.429-1.042)	0.838(0.435-1.616)	0.783(0.28-2.19)
	25th	0.915(0.858-0.975)	0.876(0.774-0.992)	0.991(0.817-1.201)	1.092(0.798-1.493)
	50th	1.003(1-1.006)	1.005(1-1.011)	1(0.992-1.009)	0.998(0.984-1.012)
	75th	0.974(0.918-1.033)	1.043(0.949-1.147)	1.01(0.88-1.158)	1.136(0.932-1.386)
	99th	0.783(0.65-0.944)	0.926(0.678-1.265)	1.026(0.639-1.648)	1.823(0.972-3.416)
Major Depressive Disorder	**1st**	1.068(0.812-1.403)	1.082(0.691-1.696)	1.233(0.619-2.457)	1.202(0.411-3.521)
	25th	0.995(0.926-1.068)	0.93(0.809-1.068)	1.005(0.81-1.247)	1.169(0.822-1.664)
	50th	1(0.997-1.003)	1.004(0.997-1.01)	1(0.991-1.01)	0.994(0.978-1.01)
	75th	0.988(0.924-1.055)	1.058(0.949-1.181)	1.018(0.87-1.191)	0.998(0.793-1.255)
	99th	0.946(0.768-1.165)	1.048(0.735-1.494)	1.054(0.616-1.802)	1.309(0.634-2.704)
Mood Disorder	**1st**	0.984(0.777-1.246)	1.001(0.682-1.467)	1.128(0.633-2.009)	1.205(0.492-2.949)
	25th	1.004(0.946-1.066)	0.948(0.843-1.066)	1.084(0.904-1.299)	1.293(0.961-1.741)
	50th	1(0.997-1.002)	1.003(0.997-1.008)	0.997(0.988-1.005)	0.99(0.976-1.003)
	75th	0.986(0.932-1.042)	1.047(0.955-1.148)	0.97(0.85-1.106)	0.977(0.806-1.185)
	99th	0.963(0.809-1.146)	1.053(0.781-1.419)	1.039(0.663-1.63)	1.474(0.801-2.712)
Self Harm and Ideation	**1st**	1.025(0.823-1.277)	0.952(0.672-1.348)	1.178(0.7-1.982)	1.392(0.651-2.98)
	25th	1.078(1.02-1.139)	1.148(1.029-1.281)	1.102(0.927-1.309)	1.235(0.922-1.653)
	50th	0.996(0.994-0.999)	0.993(0.988-0.998)	0.996(0.988-1.004)	0.991(0.978-1.004)
	75th	0.957(0.909-1.007)	0.891(0.817-0.972)	0.969(0.852-1.102)	0.91(0.751-1.102)
	99th	0.992(0.852-1.154)	0.886(0.68-1.154)	1.065(0.701-1.618)	1.057(0.587-1.904)
Suicide	**1st**	0.759(0.458-1.256)	1.2(0.53-2.717)	1.411(0.384-5.18)	1.787(0.273-11.7)
	25th	0.746(0.601-0.925)	0.857(0.596-1.235)	1.013(0.589-1.744)	1.25(0.584-2.674)
	50th	1.017(1.003-1.031)	1.011(0.987-1.035)	1.002(0.967-1.037)	0.985(0.937-1.034)
	75th	1.108(0.87-1.411)	1.014(0.68-1.511)	0.976(0.543-1.755)	0.634(0.276-1.456)
	99th	0.896(0.518-1.552)	0.785(0.316-1.946)	0.88(0.233-3.317)	0.377(0.056-2.54)

Table 3. Calculated relative risk and confidence interval for select lag periods across each applicable mental health outcome.

Buncombe County

Self-harm and suicide ideation shows a decrease in relative risk at the 1st and 25th quantiles (RR:0.352, CI:0.174-0.713 and RR:0.837, CI: 0.704-0.996, respectively) and no significant change in the later quantiles. Notably, the sample size of self-harm and ideation in

Buncombe is the lowest sample size (n=591) of all the explored variables within the study area. Results for anxiety, mood, and depressive disorders at the 0-day lag are insignificant at all temperatures.

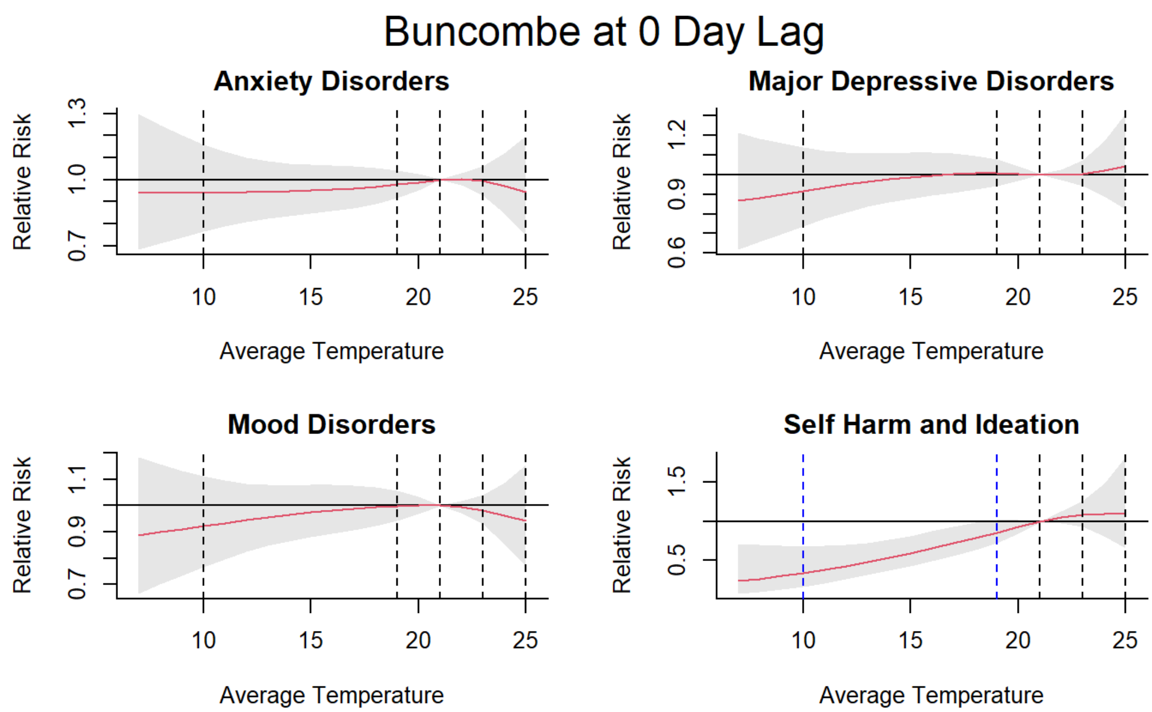

Fig. 2. The distributed lag effects of average temperature readings on the relative risk of emergency department visits for Anxiety Disorders, Major Depressive Disorders, Mood Disorders, and Self Harm and Ideation relative to the median average temperatures in Buncombe County, North Carolina. Dashed lines represent the 1st, 25th, 50th, 75th, and 99th temperature quantiles, respectively. Black lines signify insignificant changes in relative risk while blue lines indicate significantly lower risk and red lines indicate significantly higher risks.

Guilford County

All results for Guilford County were statistically insignificant at the 0-day lag. Guilford county's major depressive disorders had the highest sample size of any variable explored across the entire study area.

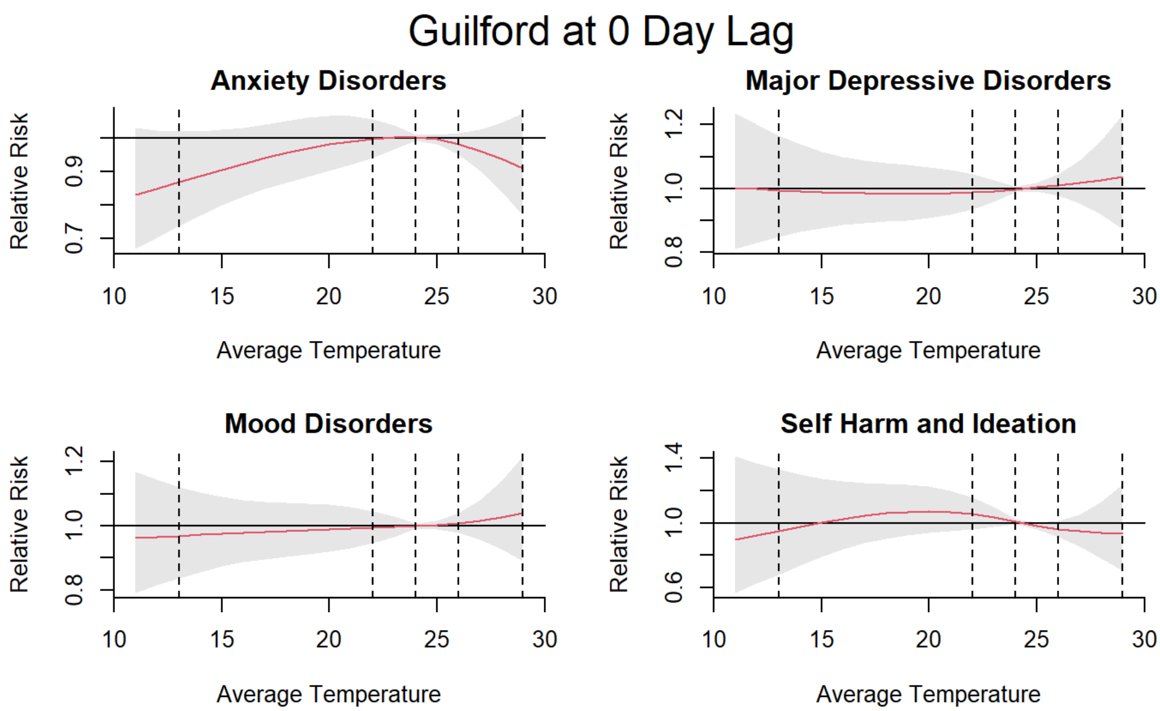

Fig. 3. The distributed lag effects of average temperature readings on the relative risk of emergency department visits for Anxiety Disorders, Major Depressive Disorders, Mood Disorders, and Self Harm and Ideation relative to the median average temperatures in Buncombe County, North Carolina. Dashed lines represent the 1st, 25th, 50th, 75th, and 99th temperature quantiles, respectively. Black lines signify insignificant changes in relative risk while blue lines indicate significantly lower risk and red lines indicate significantly higher risks.

Mecklenburg County

The relative risk of anxiety, major depressive, and mood disorders follow similar trends with lower risk at both low and high temperatures. Self-harm and ideation in Mecklenburg, however, is only lower at the 1st quantile (RR:0.738, CI:0.592-0.921). The three-dimensional plot (Figure 5) provides context to the impact of distributed lag on the temperature-mental health relationship in Mecklenburg. At the highest temperatures self-harm and ideation sees the most significant increase in relative risk at the 0-day lag period and decreases incrementally. Conversely, at the highest temperature anxiety risk incrementally increases over time. Major depressive and mood disorders see increased risk at the highest and lowest temperatures around the 10-day lag period and around Mecklenburg's median temperature (22 degrees C).

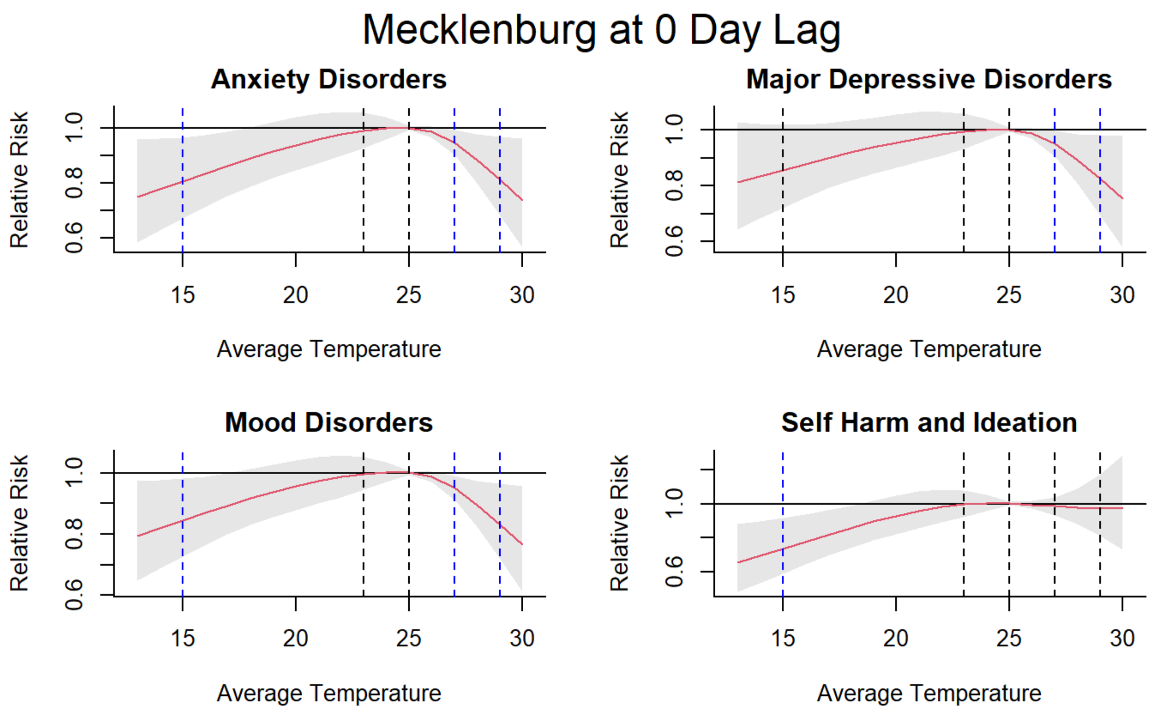

Fig. 4. The distributed lag effects of average temperature readings on the relative risk of emergency department visits for Anxiety Disorders, Major Depressive Disorders, Mood Disorders, and Self Harm and Ideation relative to the median average temperatures in Mecklenburg County, North Carolina. Dashed lines represent the 1st, 25th, 50th, 75th, and 99th temperature quantiles, respectively. Black lines signify insignificant changes in relative risk while blue lines indicate significantly lower risk and red lines indicate significantly higher risks.

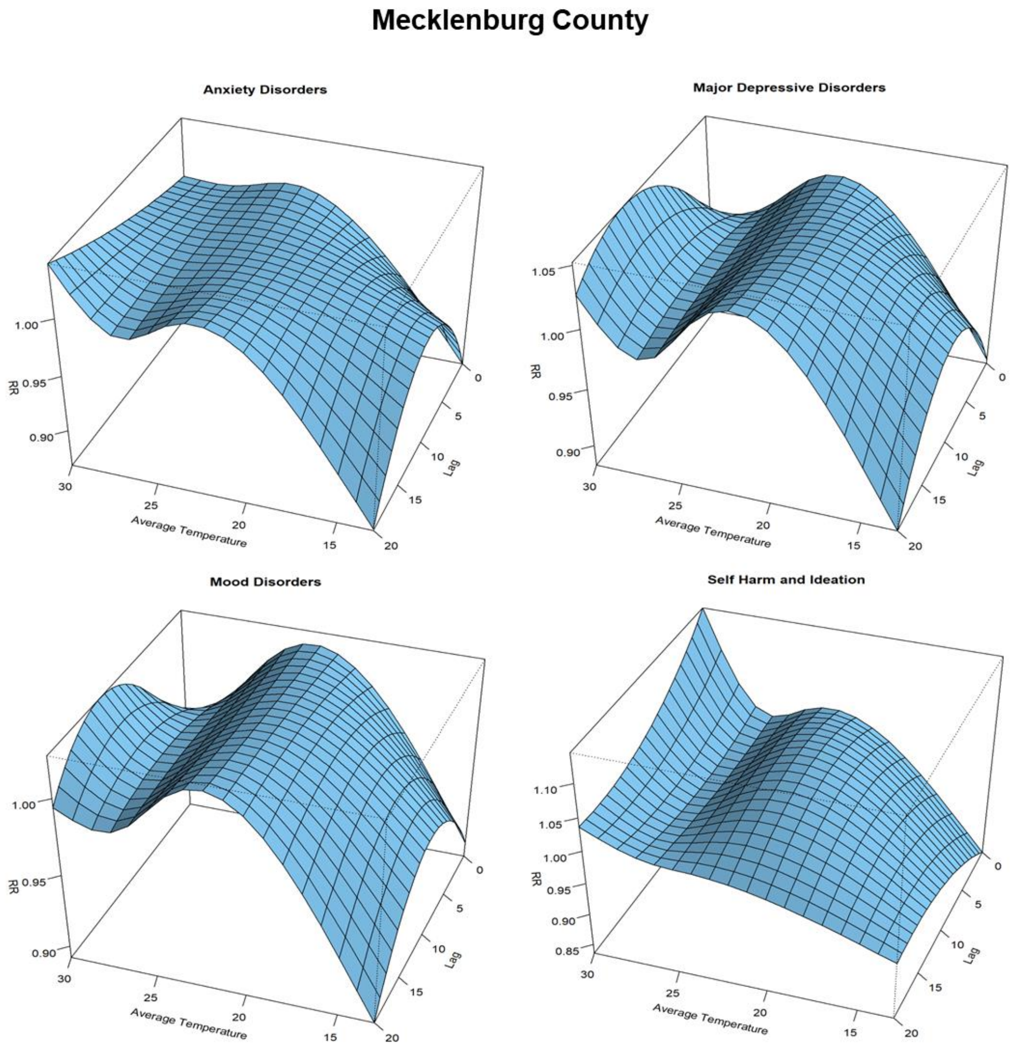

Fig. 5. The three-dimensional plot summarizes the temperature, lag, relative risk relationship of emergency department visits for Anxiety Disorders, Major Depressive Disorders, Mood Disorders, and Self Harm and Ideation in Mecklenburg County, North Carolina.

New Hanover County

Results for all explored variables in New Hanover were statistically insignificant at the 0-day lag period.

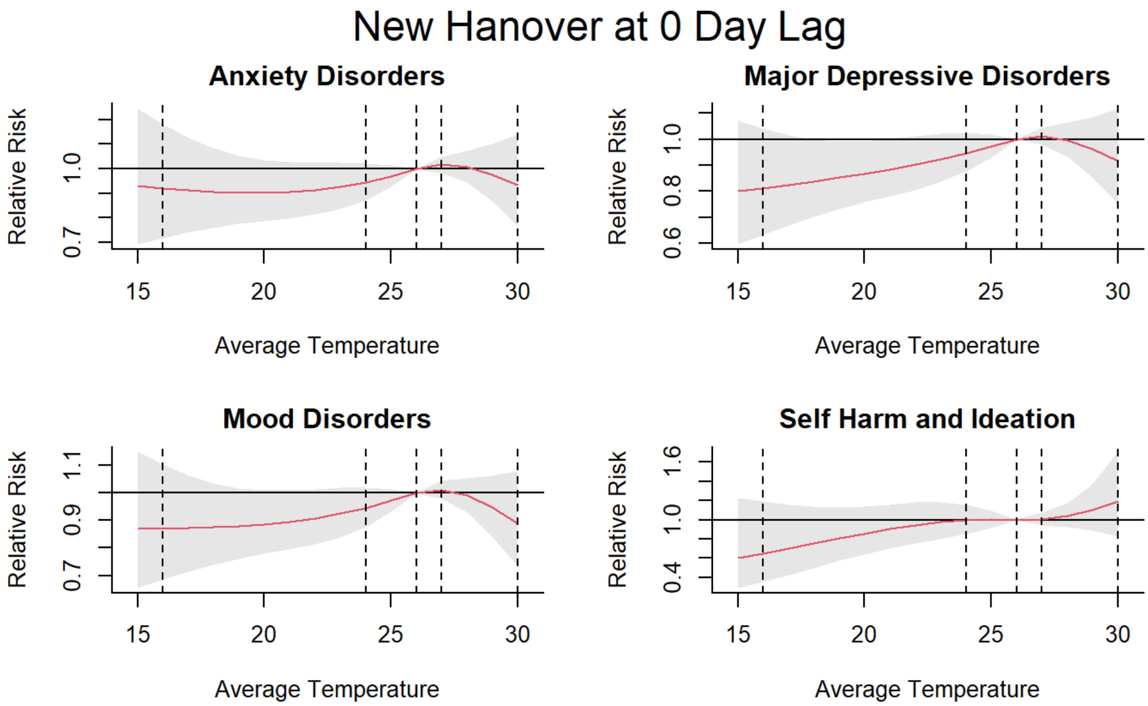

Fig. 6. The distributed lag effects of average temperature readings on the relative risk of emergency department visits for Anxiety Disorders, Major Depressive Disorders, Mood Disorders, and Self Harm and Ideation relative to the median average temperatures in New Hanover County, North Carolina. Dashed lines represent the 1st, 25th, 50th, 75th, and 99th temperature quantiles, respectively. Black lines signify insignificant changes in relative risk while blue lines indicate significantly lower risk and red lines indicate significantly higher risks.

Pitt County

Results for all explored variables in Pitt were statistically insignificant at the 0-day lag period.

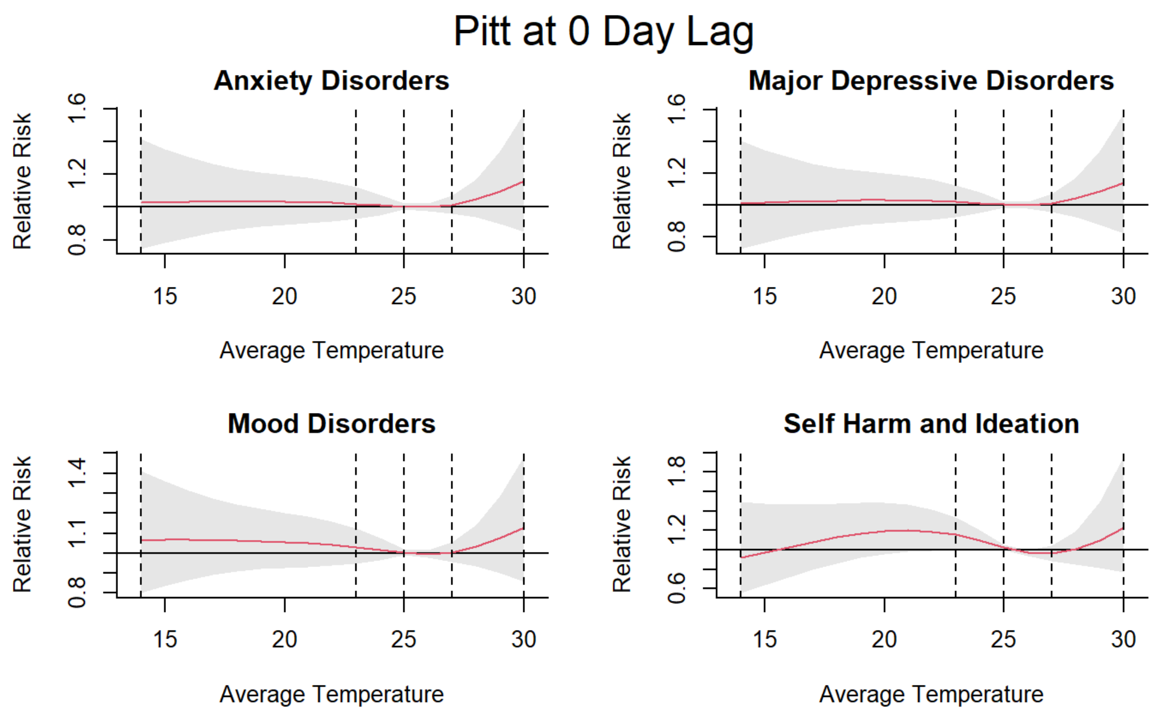

Fig. 7. The distributed lag effects of average temperature readings on the relative risk of emergency department visits for Anxiety Disorders, Major Depressive Disorders, Mood Disorders, and Self Harm and Ideation relative to the median average temperatures in Pitt County, North Carolina. Dashed lines represent the 1st, 25th, 50th, 75th, and 99th temperature quantiles, respectively. Black lines signify insignificant changes in relative risk while blue lines indicate significantly lower risk and red lines indicate significantly higher risks.

Wake County

Self-harm and ideation in Wake County show an increased risk at the 25th quantile (RR:1.078, CI:1.02-1.139) but decreased risk at the 50th quantile (RR:0.996, CI:0.994-0.999). Anxiety disorders show a decreased risk at the 25th quantile (RI:0.915, CI:0.858-0.975), an increased relative risk at the 50th quantile (RI:1.003, CI:1-1.006) and again a decreased risk at the 99th quantile (RI:0.783, CI:0.65-0.944). Mood and major depressive disorders show no significant changes in risk at the 0-day lag period.

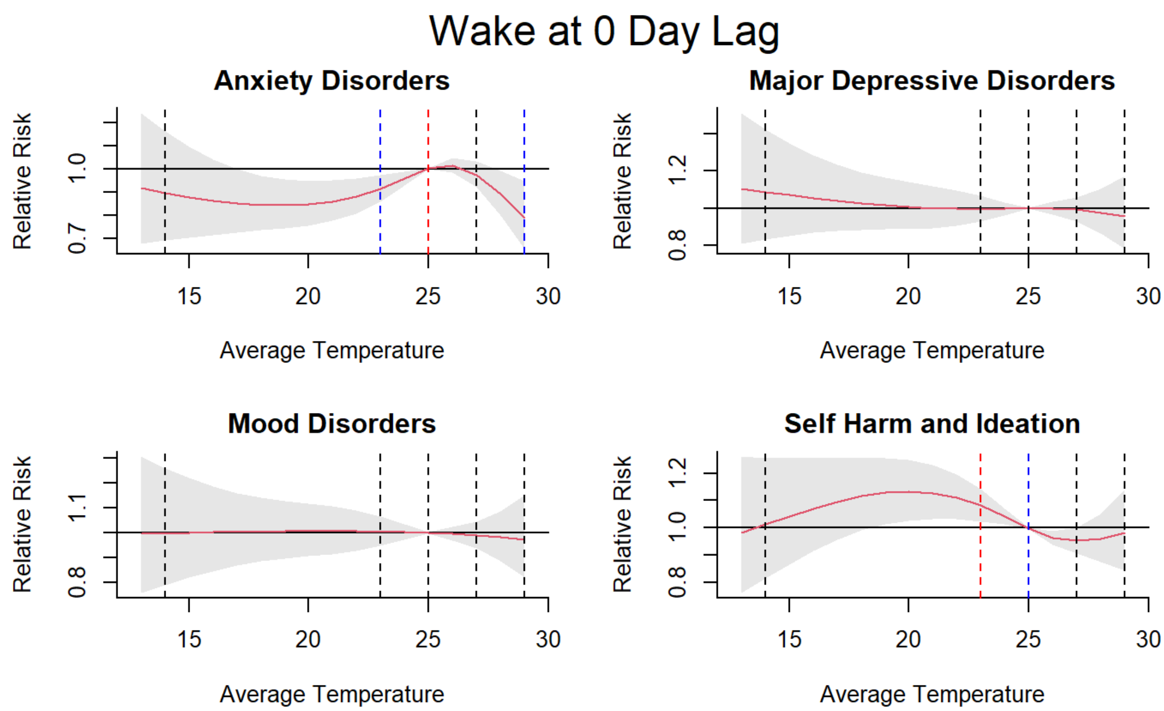

Fig. 8. The distributed lag effects of average temperature readings on the relative risk of emergency department visits for Anxiety Disorders, Major Depressive Disorders, Mood Disorders, and Self Harm and Ideation relative to the median average temperatures in Wake County, North Carolina. Dashed lines represent the 1st, 25th, 50th, 75th, and 99th temperature quantiles, respectively. Black lines signify insignificant changes in relative risk while blue lines indicate significantly lower risk and red lines indicate significantly higher risks.

Suicide

Due to the differences in the datasets the suicide data includes the annual entire year from 2005 to 2018 for Mecklenburg, Buncombe, Guilford, and Wake counties. The sample sizes for Pitt and New Hanover counties were too low to include in the DLNM. Unlike all other models, suicide favored a 20-day lag period in the sensitivity analysis. All the results for the 20-day lag period were insignificant.

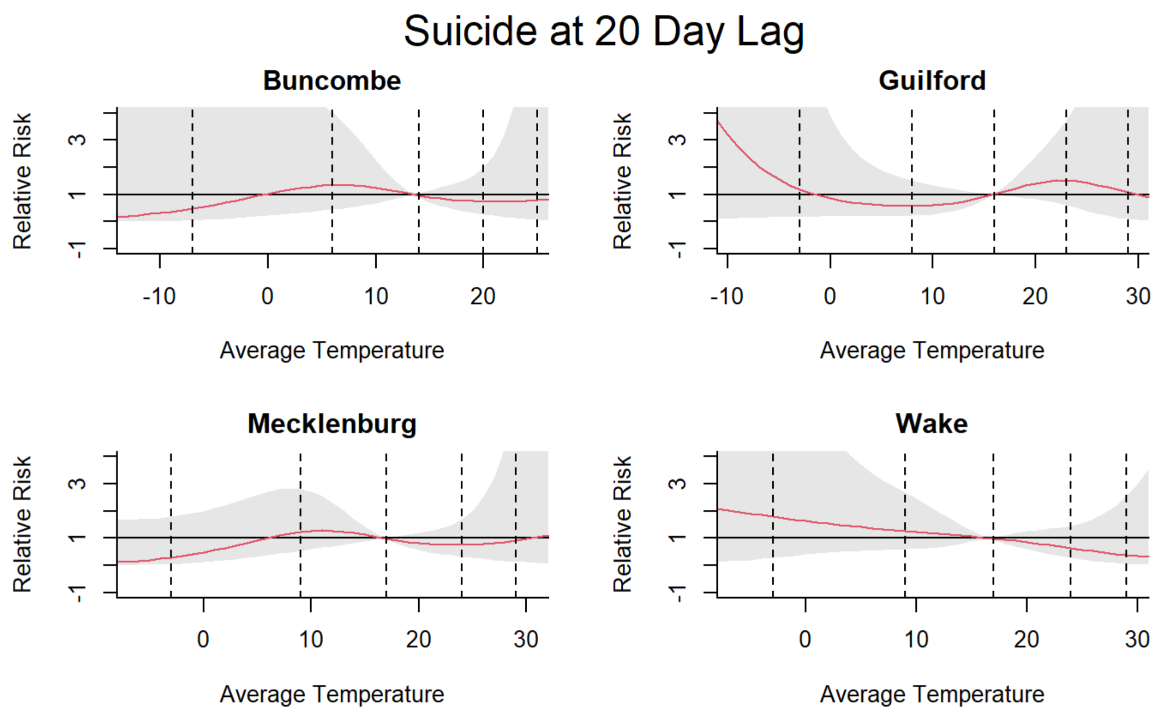

Fig. 9. The distributed lag effects of average temperature readings on the relative risk of suicide relative to the median average temperatures in Mecklenburg, Buncombe, Guilford, and Wake counties. Dashed lines represent the 1st, 25th, 50th, 75th, and 99th temperature quantiles, respectively. Black lines signify insignificant changes in relative risk while blue lines indicate significantly lower risk and red lines indicate significantly higher risks.

Discussion

This study investigates the cumulative effect of ambient temperatures on mental health in multiple urban counties across North Carolina. Our results highlight a predominately insignificant relationship between ambient temperatures and mental health outcomes in the state of North Carolina with insights into the impact of seasonal variation and the distribution of different mental health outcomes. The impact of seasonal variability may be a particularly important factor in the temperature-health relationship. This observation is supported by the presence of insignificant results in New Hanover and Pitt (coastal counties with the lowest seasonal variability) in contrast to relatively significant results in Wake (a piedmont county with the highest seasonal variability). These findings align with other US studies that find a weaker temperature-mental health relationship in geographies of similar latitudes with lower seasonal variability (Dixon and Kalksetin 2018; Sugg et al. 2019; Nori-Sarma et al. 2022). Relatively warmer annual temperatures and decreased temperature variation in subtropical regions could reduce the barriers to acclimation as seasons change.

The character of the temperature-mental health relationship changes when varying lag periods are considered. Increased symptom intensity could impair cognitive capacity and reduce an individual’s ability to fulfill basic needs such as shelter from temperature, proper hydration, adequate sleep, and other healthy habits. Self-harm and ideation at the highest temperatures in Mecklenburg display an increase in risk at the shortest lag period. The magnitude of risk for self-harm and ideation generally decreases as time passes. Anxiety disorders display the opposite trend with risk increasing as the lag period increases. Major depressive and mood disorders experience the highest risk between the 10–15-day lag periods. These varying impacts of time in the temperature-mental health relationship could be indicative of condition-specific symptoms exacerbated by cumulative exposure. Future research should consider condition-specific symptoms in the pathway of temperature-mental health relationships to better characterize changes in symptoms, mechanisms, and avenues to mitigate heat exposure.

The results for suicide are insignificant for all but one of the counties and lag periods explored. This observation is at odds with the literature where higher temperatures are associated with significantly higher relative risk of suicide (Dixon and Kalksetin 2016; Kim et al. 2019). Despite insignificant observations in the DLNMs, suicide is notably the only mental health outcome explored in this study that favored a 20-day lag period in the sensitivity analysis. The circumstances leading to suicide are unique but untreated and undiagnosed mental illnesses are the most significant predictors of suicidal behaviors (CDC 2018). The cumulative impact of temperature on other mental health outcomes could be a significant factor in the longer lag period observed for suicides. A history of self-harm and ideation has been linked to elevated risks of suicide (Olfson et al. 2018) and could serve as an important predictor for future suicidal behavior. Due to the emphasis on sample size within distributed non-linear lag models self-harm could be used as a proxy variable for the risk of suicide to expand the geographies available for research, as sample sizes were larger for self-harm and ideation ED visits than suicides. Identifying similar temperature relationships between various outcomes could address one of the key limitations in temperature-mental health research and provide insight into how various mechanisms respond to heat exposure.

Seasonally, self-harm and ideation peaked in the hottest months while anxiety, mood, and major depressive disorders peaked in coolest months. This difference in seasonal distribution is further observed in the DLNMs between self-harm and ideation and other mental health outcomes in Buncombe and Wake counties. Previous literature exploring the impact of heat exposure of specific mental health conditions found a general trend of increased risk with key condition-specific exceptions. Wang et al. (2014) found that emergency room visits for mood and affective disorders increase at high temperatures but have no significant cold temperature relationship while neurotic disorders exhibit increases at both hot and cold temperatures. Nori-Sarma et al. (2022) found that emergency room visits for substance abuse, anxiety, stress, somatoform, mood, schizophrenia, schizotypal, delusional, childhood-onset behavior disorders, and self-harm significant increase with extreme heat exposure while adult personality and behavior disorders do not significantly increase with extreme heat exposure. Differences in the temperature-mental health relationship between outcomes remain a key research gap and emphasize the importance of understanding how environmental factors interact with diverse disease pathologies.

The physiological and psychological mechanisms behind seasonal patterns in mental health crises are still unknown, though a variety of explanations have been suggested. Some mental health disorders and medications have been linked to the disruption of neurotransmitters important in maintaining thermoregulation (Shiloh et al. 2001; Martin-Latry et al. 2007; Sung et al. 2011). Several studies have linked temperature and sunlight to changes in the serotonin pathway (Ljubicic et al. 2007; Ogawa et al. 2014), suggesting a possible pathway to increased rates of suicide and major depressive disorders. Melatonin, a hormone strongly associated with sleep, displays a negative association with sunlight exposure (Petridou et al. 2002). In addition to environmental factors, individual stressors have been suggested to alter the temperature-mental health relationship. People of lower socioeconomic status may have reduced access to environmental features that can help mitigate temperature exposure such as green space and air conditioning (Semenza et al. 1999; Nutsford et al. 2013). Annual periods of high stress events such as the beginning of a school year or harvest seasons occur in late spring and summer (Sun et al. 2011). Impaired cognition, a common side effect of mental health disorders, can decrease a person's capacity to properly respond to environmental stressors (Hansen et al. 2008). These explanations identify changes in brain chemistry, reduced access to appropriate shelter, and patterns of high stress, all of which are thought to contribute significantly to poor mental health outcomes (Durkheim 1951; Wang et al. 2014; Kim et al. 2016). It is likely that several of these mechanisms, and some yet unexplored, simultaneously contribute to the temperature-mental health relationship. Understanding these cultural and pathologic pathways can help identify important environmental variables and at-risk populations in future studies.

Strengths and Limitations

To the best of our knowledge this study is the first to look at the temperature-mental health relationship across North Carolina. The state's diverse geography and data availability enable us to explore the temperature-mental health relationship of five health outcomes within several climate regions. The study design explored the use of DLNM to take into account the cumulative exposure, delayed impact, and nonlinear characteristics of the temperature-mental health relationship. Since the development of the DLNM design this model has widely been preferred in environmental health literature when compared to a linear time series analysis. An exhaustive sensitivity analysis was applied to the models. The impact of varying lag, temperature splines, degrees of freedom, and model structure were assessed in over 500 iterations. Those that performed best under the quasi-Akaike information criterion (qAIC) were used to determine the structure of the final model.

The temperature-mental health relationship is inherently complex, and this study has some important limitations. Our admissions data was aggregated to the county level and was unable to include personal patient history. Individual factors such as gender, age, and mental health history have strong effects on the relationship between temperature exposure and mental health outcomes (Preti and Miotto 1998; Bouchama et al. 2007; Kim et al. 2011; Kim et al. 2016) but were not explored in this study. Prior studies have shown that exposure to air pollution, high humidity, and solar radiation reshape the temperature-mental health relationship (Kim et al. 2010; Lim et al. 2012; Vida et al. 2012; Pun et al. 2016; Wortzel et al. 2019). This study focuses on ambient average temperature exposure without the inclusion of other environmental stress factors. Due to recent changes in the way that emergency departments in North Carolina report data within the ICD coding system our data was limited to a three-year period. The small sample size available in the data restricted the range of mental health outcomes and geographies appropriate for analysis. This limitation was somewhat mitigated by the appearance of similar trends in counties with more complete datasets, but final emergency room models were all limited to the three-year period in the interest of model uniformity and comparability. Lastly, similarities between the symptoms of mental health illnesses can lead to misclassification within the data (Lee et al. 2018).

Future Research

There are many uncertainties regarding the relationship between temperature and mental health. While all measures of emotional well-being are negatively associated with increased temperatures, the strength of association varies greatly (Noelke et al. 2016). Several geographically diverse environmental and demographic variables are thought to have influence over relative risk. Local seasonality, humidity, air pollution, age, gender, mental health history, socio-economic status, and urban-rural divides are commonly proposed confounders. Due to the importance of sample size in the efficacy of distributed nonlinear lag models (Dixon & Kalkstein 2018) it can be difficult to explore all of these variables concurrently. In an effort to better understand the mitigating factors of temperature-health relationships, future research should embrace the inherent complexity of the problem and explore a multivariate analysis wherever possible (Gabreab 2018). Applying a more comprehensive model to a wide range of climate regions will help contextualize the temperature-mental health signal and give insight into the elusive causal pathways behind poor mental health outcomes.

There is evidence that the context of the built environment could have an impact on the temperature-mental health relationship. Son et al. (2019) suggests that population density, housing quality, water features, air conditioning, and green space could all help mitigate community level heat-health risk. Mitigation tools in the built environment, such as air conditioning (AC), are more prevalent in southern states like North Carolina with estimates of AC prevalence as high as 95% for households either owning a window unit or central air system (US EIA 2015). Recreational areas and green spaces can significantly mitigate poor mental health outcomes by encouraging recreation, socialization, and community cohesion (Nutsford et al. 2013). Increasing accessibility to these areas present an important opportunity for planners to address the temperature-mental health relationship at the community scale. Future studies should examine access to these features as they could reduce the impact of temperature exposure.

There are a number of weather components that contribute to temperature exposure including ambient air temperature, humidity, and solar radiation (Kim et al. 2010; Lim et al. 2012; Vida et al. 2012; Pun et al. 2016; Wortzel et al. 2019). The combined contributions of these factors comprise an ‘apparent temperature,’ commonly known as the heat index. Temperature-suicide literature focuses on one or more of these component variables, most often ambient air temperature and/or humidity. While heat indices are popular and suitable to represent the combined hot effect of temperature and humidity it is not an ideal indicator at low temperature because sweat evaporation is not an important avenue of heat transfer from the human body at cooler air temperatures (Anderson et al. 2013). Recognizing the limitations inherent in the common heat index, the Universal Thermal Climate Index (UTCI) was developed using state of the art thermo-physiological and heat exchange theory (Jendritzky et al. 2011). Despite being created specifically for temperature-health research, the UTCI is underrepresented in temperature-suicide literature. The exploration of each weather component’s independent and cumulative contribution to temperature exposure may help explain some of the variability observed in climate-suicide relationships.

Conclusions

This study exhibits a predominantly insignificant relationship between temperature and poor mental health outcomes across North Carolina, with some exceptions in Buncombe and Wake counties. Insignificant relationships in counties with the lowest temperature ranges contrast with significant relationships in counties with the highest temperature ranges, suggesting that local climate variability could have a significant impact on the temperature-mental health relationship. Mental health outcomes exhibit different seasonal distributions and the temperature exposure relationship changes across lag periods. The number of ER visits for self-harm and suicidal ideation peak in the hottest months and risk is greatest at following acute exposure to hot ambient temperature. Anxiety, mood, and major depressive disorders peak in early and late summer and risk is greater following periods of prolonged temperature exposure. Heat adaptive features in the built environment and condition-specific symptoms could impact the adaptive capacity of residents and explain some of the temporal variation in the temperature-mental health relationship. Future research should focus on climatologically and demographically diverse locations to better characterize the impact of various confounding factors.

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Appendix:

Lag	Anxiety Disorders	Major Depressive Disorders	Mood Disorders	Self Harm and Ideation	Anxiety Disorders	Major Depressive Disorders	Mood Disorders	Self Harm and Ideation
	Buncombe				**New Hanover**			
0	148.8	136.9	146.2	298.2	183.8	188	177.5	244.1
6	179	160.5	177.4	309.6	210.5	210.6	207.9	256.7
13	178	159.2	176.4	304.7	208.3	208.2	203.6	250.4
20	174.4	158.3	174.6	301.3	210.8	210.4	208.5	244.5
	Guilford				**Pitt**			
0	124.6	123.6	126.4	166.6	157.2	161.8	152.1	236.6
6	145.4	144.8	152.1	178.9	175.3	182.2	175.8	249.7
13	145.2	142.3	150.5	175.2	173	180.7	174.6	247.1
20	144.7	140.4	149.3	173.2	171.7	179.1	173.6	245.2
	Mecklenburg				**Wake**			
0	136	131.6	131.2	136.1	139.9	150.1	136.7	128.6
6	162.2	154.5	158.6	152.6	157.1	167.5	157.3	141.8
13	164.1	156.1	160.7	151.1	156.1	166.3	155.6	140.7
20	164.3	153.5	158.4	150	154.9	165.7	155.3	139.5

Figure A1. Results from the qAIC when varying the maximum lag period

	Buncombe		**Guilford**		**Mecklenburg**		**Wake**	
	Suicide	**Temp (°C)**	**Suicide**	**Temp (°C)**	**Suicide**	**Temp (°C)**	**Suicide**	**Temp (°C)**
January	34 (7%)	1.72	44 (8%)	4.01	67 (9%)	5	58 (8%)	4.81
February	37 (7%)	3.55	52 (9%)	5.8	68 (9%)	6.98	44 (6%)	6.39
March	54 (11%)	7.8	62 (11%)	10.06	61 (8%)	11.1	77 (10%)	10.29
April	45 (9%)	12.65	43 (7%)	15.12	54 (7%)	16	75 (10%)	15.73
May	42 (8%)	16.76	57 (10%)	19.58	83 (11%)	20.46	77 (10%)	20.19
June	49 (10%)	20.86	50 (9%)	24.15	68 (9%)	24.99	62 (8%)	24.76
July	50 (10%)	22.02	44 (8%)	25.64	53 (7%)	26.33	55 (7%)	26.37
August	41 (8%)	21.72	54 (9%)	25.09	59 (8%)	25.87	77(10%)	25.74
September	52 (10%)	18.75	54 (9%)	21.54	78 (10%)	22.61	51 (7%)	22.29
October	39 (8%)	12.82	36 (6%)	15.46	46 (6%)	16.19	69 (9%)	16.09
November	28 (6%)	7.15	43 (7%)	9.32	54 (7%)	10.04	66(9%)	9.91
December	37 (7%)	4.47	44 (8%)	6.53	65 (9%)	7.5	59 (8%)	7.33

Figure A2. Temperature and distribution of suicide from 2006-2018.

Vita

Tyler Minor was raised in the small town of Camden, North Carolina. In his junior year of high school, he moved to Durham, North Carolina to attend the North Carolina School of Science and Mathematics. This opportunity inspired a passion for science and community which has guided his academic career since. After graduating in 2016, Tyler moved to Boone, North Carolina to attend Appalachian State University.

In his time as an undergraduate student Tyler studied environmental science with a minor in geology. He focused his extracurricular opportunities on leadership and community service, working as a resident assistant for much of undergrad and serving on the executive board of several campus and state organizations. Tyler graduated with a Bachelor of Science in Environmental Science in May 2020. Tyler continued his education as a graduate student in the Department of Geography and Planning in August 2020. After being introduced to Dr. Maggie Sugg, Tyler was presented with several opportunities to work on research projects regarding public health and climate. Tyler will graduate with a Master of Arts in Geography in May 2022.