Title: The impact of climate change on transmission season length: West Nile virus as a case study

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Abstract

Climate change is accelerating the spread of vector-borne diseases like West Nile virus (WNV), which is highly temperature-sensitive. WNV is the most widespread mosquito-borne disease in the continental United States, with over 2,400 reported cases in 2024. In New York State (NYS), where WNV first emerged in the US, temperatures have risen over 1.4°C since the early 1900s. While temperature's role in WNV transmission is established, its effect on season length is less clear. This study asks: (1) Has the WNV season lengthened in NYS over the past 25 years? (2) Is a longer season linked to higher WNV incidence in mosquitoes and humans? and (3) Are these changes associated with shifts in the timing of infection onset and termination in hosts? We

integrated daily county-level temperature, mosquito surveillance, and human case data from 1999–2024. Our results show that based on temperature suitability, the WNV season has extended by an average of 24.8 days—starting 4 days earlier and ending 20 days later. Longer seasons are positively associated with greater WNV prevalence in both mosquitoes and people. These findings underscore how climate change is reshaping the phenology and burden of vector-borne disease. Many vector-borne diseases may face amplified risks as transmission seasons lengthen, highlighting the need for adaptive public health responses.

Introduction

Across the globe, temperature is increasing; since 1999, there has been a global average increase of 0.4°C[1]. Climate change has been shown to affect many infectious diseases, and vector-borne diseases are particularly susceptible to thermal changes because mosquitoes are ectothermic organisms. Temperature affects several key mosquito life history traits—such as survival, blood feeding, vector competence, and development—as well as pathogen replication, all of which are essential for disease transmission[2]. Vector-borne diseases account for more than 17% of all infectious diseases, causing more than 700,000 deaths annually[3]. Vector-borne diseases are especially responsive to anthropogenic changes, and rising temperatures can influence disease risk[4]. Although a large body of research has documented impacts of temperature on vector-borne disease transmission[4–7], very few studies have investigated how climate warming has affected the transmission season in temperate environments[8–10], where transmission is limited by cool temperatures in the spring and fall. Because infectious disease dynamics are nonlinear, with transmission peaking at an intermediate

temperature and declining at extreme cold and hot temperatures, seasonal epidemics that begin earlier and extend later into the season can amplify disease burden.

West Nile virus (WNV), a mosquito-borne arbovirus, emerged in the Western Hemisphere in 1999, with New York State (NYS) at the epicenter of the outbreak. In NYS, the average temperature has increased by nearly 1.4°C from 1901 to 2022[11,12]. The thermal suitability range for WNV transmission by *Culex pipiens*, the primary vector in NYS, is between 16.7°C and 33.9°C[13]. This implies that the time at which seasonal temperatures become suitable for WNV transmission governs the outer bound on the transmission season, and that these seasonal thermal suitability limits may be changing with climate warming. Climatic factors such as temperature, precipitation, and relative humidity are known drivers of WNV transmission under climate change[4,6,13–17]. Warmer temperatures, elevated humidity, and heavy precipitation contributed to an increased rate of human WNV infection in the United States (U.S.) during the early 2000s[18]. Drought has also been identified as a key driver of WNV transmission dynamics in the U.S.[19]. In the Southeastern U.S., dry and hot spring/summer conditions, along with increased temperature and rainfall in late summer/fall, have been shown to lengthen the WNV transmission season[20]. In the Northeastern U.S., WNV is predicted to become more geographically widespread due to climate change[10,21]. Although the impact of temperature on WNV transmission is well described[7,13,19], its influence on the length of the WNV transmission season and association with human incidence has yet to be fully elucidated in NYS or elsewhere.

In this study, we examine the impact of climate change on the transmission dynamics and seasonal duration of vector-borne diseases using WNV in NYS as a case

study. Using temperature, mosquito surveillance, and human case data from 1999 to 2024, spanning the entire time since WNV was introduced to the US, we assess the influence of climate change on WNV transmission season length in NYS. Specifically, we address two questions: (1) Has the WNV transmission season length increased in NYS? (2) Are longer transmission seasons associated with increased WNV incidence in mosquitoes and humans? and (3) Are these changes associated with shifts in the timing of infection onset and termination in hosts? The goal of this study is to outline the effect of rising temperatures on WNV transmission season length, to help public health officials better prepare for future transmission seasons by adjusting the timing of surveillance and vector control activities. Our results illustrate the broad potential for climate warming to extend vector-borne disease transmission seasons, particularly in temperate regions where they are limited by cool temperatures.

Methods

Temperature Data

Daily temperature data were derived from GRIDMET[22] using a downloader tool[23]. GRIDMET is a gridded surface meteorological dataset that covers the continental U.S. mapping surface weather variables at a ~4-km resolution. We used data daily, county-wide, temperature data from 1999-2024. This data set combines two data sets, temporally rich data from the North American Land Data Assimilation System Phase 2 (NLDAS) and spatially rich data from parameter elevation regression of the independent slopes model (PRISM). Data were downloaded by county; data analysis was performed in R 4.3.2[24] and visualization was performed in R and Prism 10.4.1. Temperature data was filtered to

include days where the average daily temperature was ≥16.7°C, the thermal minimum for transmission estimated by previous studies[17,25], and that were within a 13-day window of another day ≥16.7°C (to remove single-day temperature outliers and span the timeline of mosquito development). Season length was measured by calculating the number of days between the first and last days within our filter that were ≥16.7°C. We did not use an upper bound as average temperatures do not generally reach the temperature maximum of WNV transmission (33.9°C)[7].

To calculate changes in temperature-suitable transmission dynamics, we fit three linear regressions per county: (1) temperature-suitable season length by year, (2) temperature-suitable first day of transmission season by year, and (3) temperature-suitable last day of transmission season by year (e.g., Eq. 1).

$$Y = \beta_0 + \beta_1 Year + \varepsilon \qquad \text{Eq. 1}$$

We used linear regression to estimate the y-intercept (β_0) and average rate of change (β_1) over time (in years) for each response variable Y (i.e., season length, first day, and last day of transmission). This approach captured the underlying linear trend across the study period (1999–2024) and helped reduce the influence of short-term anomalies or noise in the data. For each county, we used the fitted regression model to predict the value of each transmission variable in both 1999 and 2024. We then calculated the total change over time by taking the difference between these two predicted values. We used the model-based predictions, rather than raw observed values in 1999 and 2024, to ensure that our estimates of change reflect long-term trends rather than being overly influenced by outlier years or transient fluctuations at either endpoint.

To obtain historical temperature data, we sourced data from the WorldClim version 2.1 climate data[26] spanning from 1970-2000. These data include monthly climate data for mean temperature at a spatial resolution of 10 minutes. This data was then analyzed and visualized in R[24] to determine the average historical temperature in each county in NYS. The R code used for these data analyses and those here after can be found at https://github.com/Rachellfay/WNV-Season-Length.

Mosquito Surveillance Data

Data was compiled from mosquito trapping and testing across NYS as a part of the Arbovirology surveillance program, which has received samples from 45 of the 62 counties in the state, although participating counties vary by year. These data exclude Bronx, Kings, New York, Queens, and Richmond counties, which conduct their own mosquito surveillance annually. Mosquito surveillance was completed as previously reported[27–29]. Briefly, *Culex* spp. mosquitoes were collected in Centers for Disease Control (CDC) light traps by NYS county health departments and pools were submitted to the NYS Arbovirus Laboratory for processing and testing. Mosquito sampling was conducted between May and October from 2000 to 2024, with sampling intervals ranging from every 2 to 8 weeks, depending on the year and location. WNV-positive mosquito pools were identified using real-time qRT-PCR assay as previously described[30]. *Culex pipiens* and *Culex restuans* are pooled before testing because they are morphologically indistinguishable. WNV prevalence was determined using maximum likelihood estimation (MLE) based on mosquito surveillance pool sizes using an Excel Add-In (https://www.cdc.gov/westnile/resourcepages/mosqSurvSoft.html). County-level graphs were

made by filtering data to only include counties where mosquito surveillance occurred for 10 or more years. Data analysis was performed in R[24] and visualization was performed in R and Prism 10.4.1.

Human WNV Data

Human WNV case data were obtained from the New York State Department of Health Bureau of Communicable Disease Control and the Centers for Disease Control annual county data records[31], excluding Bronx, Kings, New York, Queens, and Richmond counties, where mosquito surveillance data were not available. Human WNV cases were identified either by serology or molecular testing, as well as de-identified, aggregated, and anonymized data. Cases were aggregated by year; data analysis was performed in R[24] and visualization was performed in R and Prism 10.4.1. Additionally, human WNV case data were filtered to identify the first and last human WNV cases each year within a 14-day window of another case to avoid outliers. A sensitivity analysis was performed to evaluate changes in the R^2 and p-value with changes in detection window ranging from 10-20 days, showing that the results were robust to windows greater than 13 days (Table S1).

Results

Temperature Data

To assess the impact of temperature on West Nile virus (WNV) transmission season length, temperature data were filtered by days ≥16.7°C, which falls within the previously estimated thermal suitability range for WNV transmission by *Culex pipiens*

populations in NYS[13]. Hereafter, we refer to the number of days above the thermal suitability threshold as the 'transmission season.' The average transmission season length has significantly increased since 1999 (Fig. 1A and B; simple linear regression, $p < 0.05$). Although the increase varies by county (Fig. 1C), on average, the transmission season has extended by 24.8 days from 1999 to 2024.

Over the past 25 years, the transmission season has begun significantly earlier and ended significantly later statewide (Fig. 2A, 2C; simple linear regression, $p < 0.05$). Although the extent of transmission season advance varies across counties, the season started an average of 4 days earlier from 1999 to 2024 (Fig. 2B). Additionally, the transmission season now ends later than it did in the past; in 2024, it ended an average of 20 days later than in 1999 (Fig. 2D). However, the length of the extension varies by county. To determine if historically cooler counties had larger differences in season length, we analyzed historical temperature data from 1970-2000 and plotted this against changes in season length. We found a quadratic relationship between change in season length and historical temperature on a county scale, where the greatest increase in season length has occurred in areas with an 8.5ºC average historical temperature (Fig. 2E; quadratic regression, $p < 0.001$).

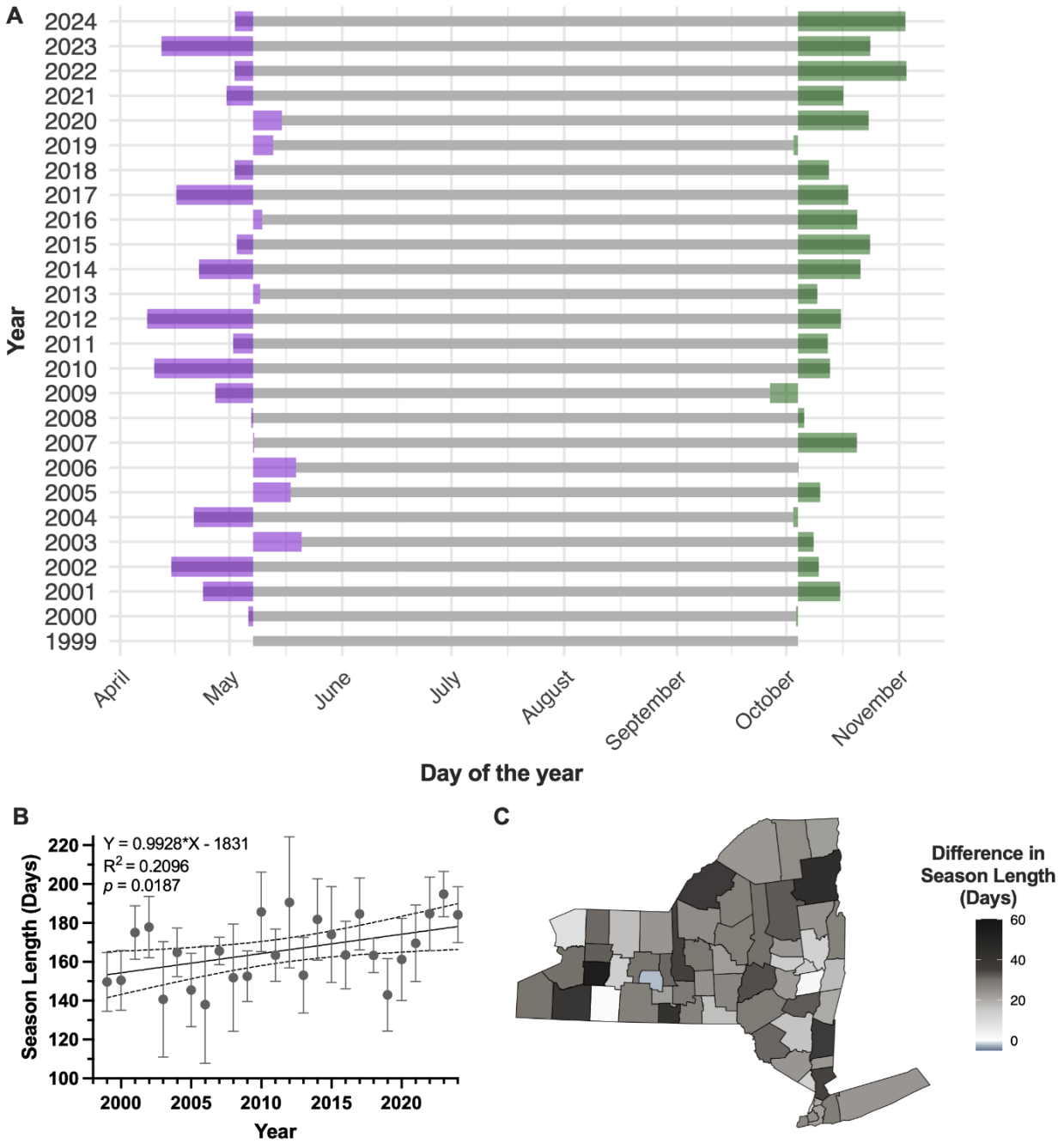

Fig 1. Change in WNV season length from 1999-2024. **A**) Summary of annual average season length across NYS across all counties. Gray denotes the 1999 season determined by filtering days ≥16.7°C, purple denotes the early season anomaly compared to the 1999 season, and green denotes the late season anomaly compared to the 1999 season. **B**) Average season length annually across NYS and the standard deviation in season length across all counties per year. Showing the mean, SD, and 95% confidence interval (simple linear regression p=0.0187). **C**) Map by county of the difference in season length between 1999 and 2024.

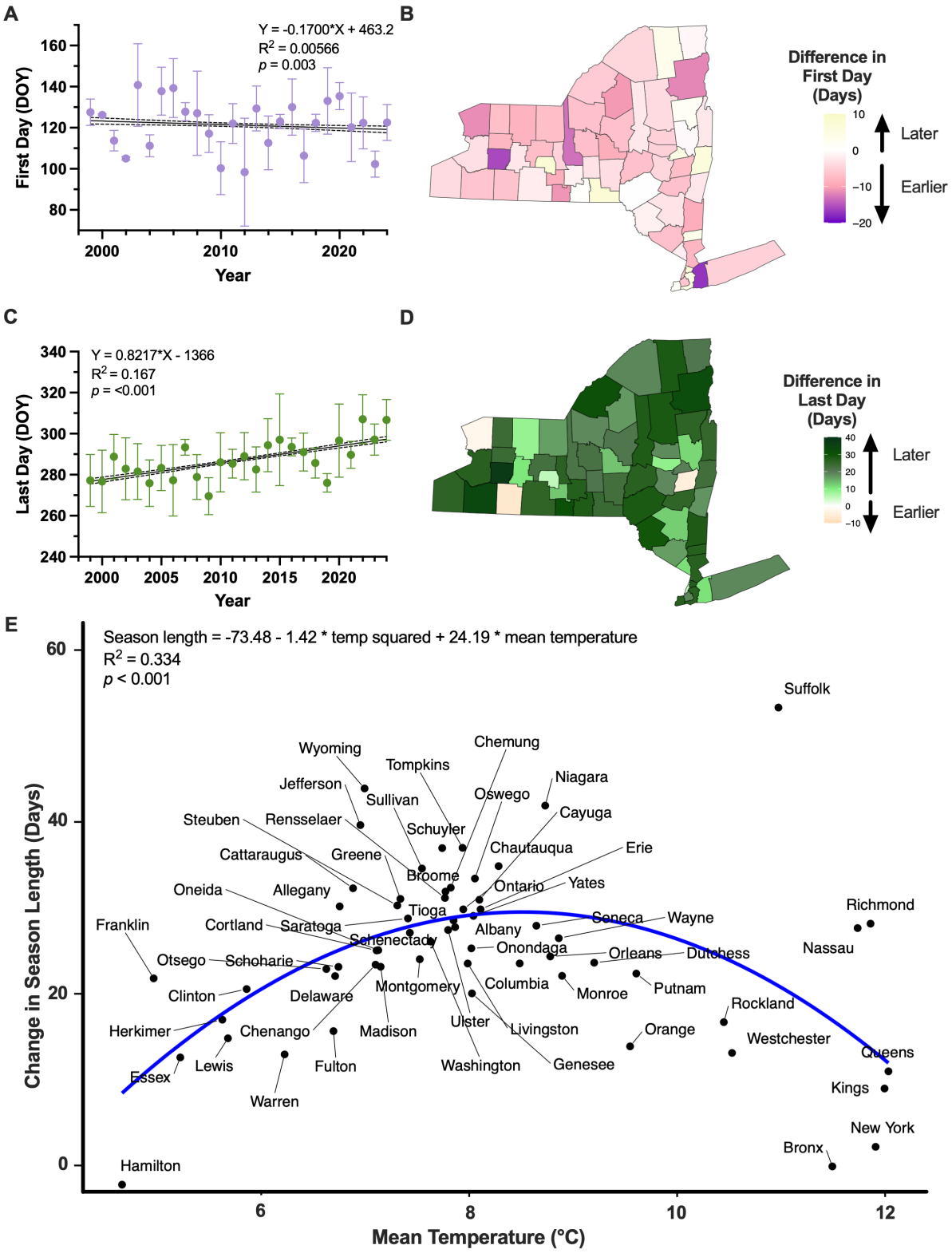

Fig 2. The difference in the first (**A**-**B**) and last (**C**-**D**) day of the season and total season length by historical temperature (**E**). (**A**) First day ≥16.7°C annually statewide, showing the mean, SD, and 95% confidence interval (simple linear regression *p*=0.003). (**B**) Map

by county of the difference in the first day of the season from 1999 compared to 2024. (**C**) Last day ≥16.7°C annually statewide, showing the mean, SD, and 95% confidence interval (simple linear regression p=<0.0001). (**D**) Map by county of the difference in the last day of the season from 1999 compared to 2024. **E**) Quadratic regression model describing the relationship between season length and historical temperature on a county scale, with points labeled by county name (quadratic regression $p < 0.001$ and season length = -73.48 - 1.42 * temp squared + 24.19 * mean temperature).

Mosquito Infection Data

We hypothesized that longer transmission seasons would result in higher average infection prevalence in mosquito surveillance pools. To test this relationship, county-level mosquito surveillance data were analyzed and compared with the state-wide average transmission season length. WNV prevalence was calculated using maximum likelihood estimation for all *Culex* spp. mosquito pools (Fig. 3A; simple linear regression, $p < 0.05$). We calculated the season length for each county with at least 10 years of surveillance data and compared these lengths to the prevalence of WNV-positive mosquito pools. Longer transmission seasons were associated with an increased number of WNV-positive mosquito pools statewide (Fig. 3A) and in Erie and Suffolk counties (Fig. 3B and C; simple linear regression, $p < 0.05$), but not in five other counties analyzed (Fig. S1; $p > 0.05$).

Given that longer transmission seasons are associated with increased WNV incidence in mosquitoes, we next investigated whether the first WNV-positive mosquito pool occurs earlier in the year. Statewide, longer transmission seasons were significantly associated with earlier detection of the first WNV-positive mosquito pool of the season (Fig. 3D; simple linear regression, $p < 0.05$). Moreover, a significant negative association between the timing of the first WNV-positive pool and the length of the season was observed in both Rockland and Suffolk counties (Fig. 3E and F; simple linear regression, $p < 0.05$), while no such relationship was found in five other counties analyzed (Fig. S2;

$p > 0.05$). Contrary to our expectations, we found no significant trend in the timing of the last WNV-positive mosquito pool annually, nor was there a significant association between longer transmission seasons and later mosquito transmission activity (Fig. S3; $p > 0.05$). However, because cessation of seasonal WNV surveillance is contingent on resource allocation rather than WNV activity or temperature, it is likely that late-season WNV positivity of mosquitoes has been missed.

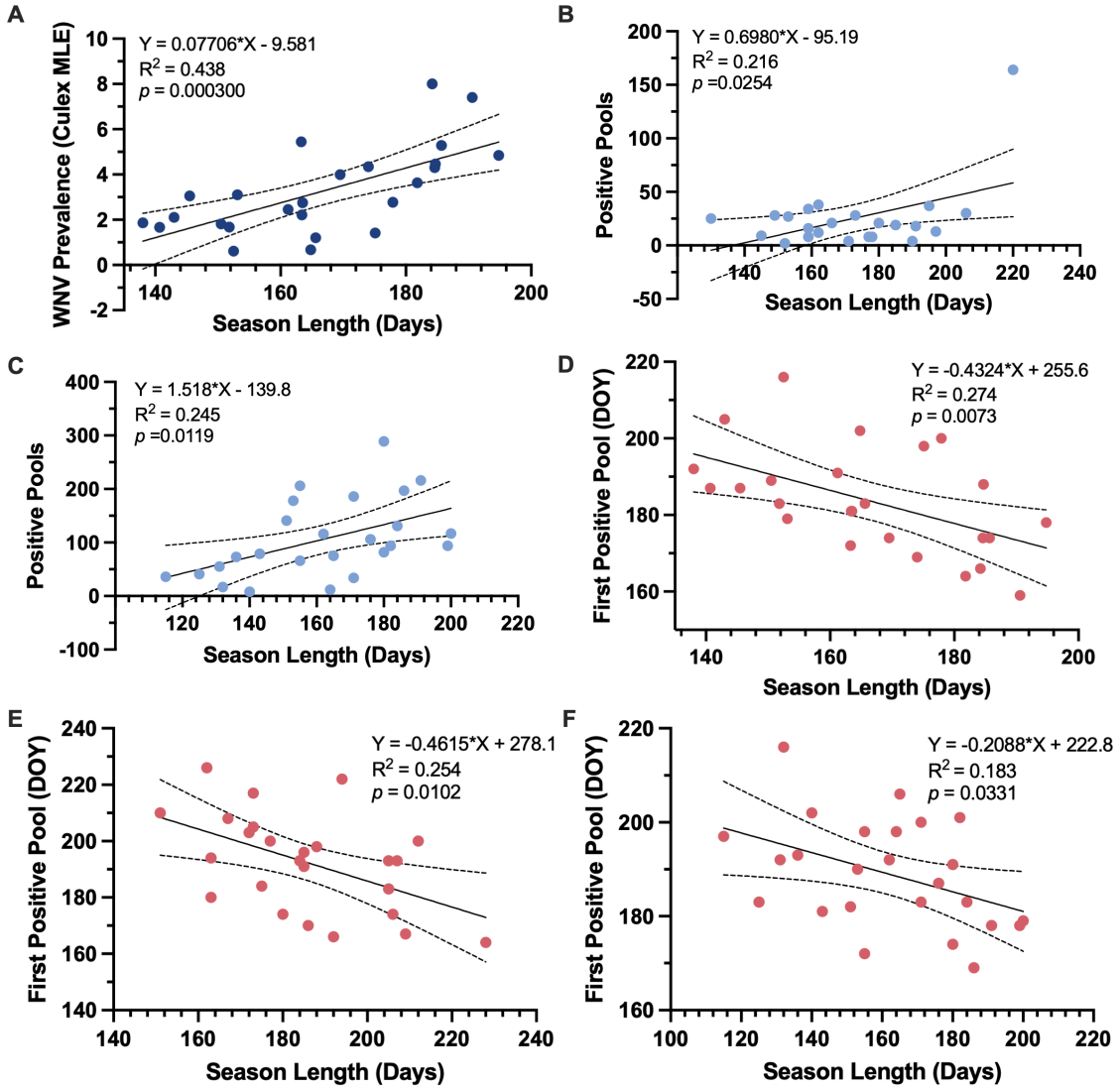

Fig 3. The relationship between WNV prevalence in mosquitoes and season length. **A**) Annual WNV prevalence (maximum likelihood estimation) versus average season length statewide (simple linear regression p=0.0003). **B**) Erie County number of WNV-positive

mosquito pools versus transmission season length (simple linear regression p=0.0254). **C**) Suffolk County number of WNV-positive mosquito pools versus transmission season length (simple linear regression p=0.0119). **D**) First positive mosquito pool statewide versus annual average statewide season length (simple linear regression p=0.0073). **E**) Rockland County first positive mosquito pool counts versus transmission season length (simple linear regression p=0.0102). **F**) Suffolk County first positive mosquito pool counts versus transmission season length (simple linear regression p=0.0331). (Note that the y-axis differs among panels.)

Human Case Data

To investigate the relationship between the duration of the WNV transmission season and the occurrence of human infections, we used statewide human West Nile virus (WNV) case data obtained from the CDC. Through a simple linear regression, we identified a statistically significant positive correlation between the length of the transmission season and the number of reported human WNV cases (Fig. 4A; $p < 0.05$). The coherence of longer transmission seasons (based on thermal suitability) with higher rates of infection in mosquitoes with higher human caseloads illustrates the potential public health implications of prolonged periods of virus activity. We assessed the relationship between the timing of the first human WNV case and transmission season length and found that human cases tend to occur earlier during longer transmission seasons, with cases being diagnosed 31 days earlier (Fig. 4B; $p < 0.05$). Similarly, we found that longer seasons are associated with later occurrences of the last human WNV case statewide, with cases being diagnosed 46 days later (Fig. 4C; $p < 0.05$). Together, these findings indicate that extended transmission seasons are linked to increased WNV activity in humans.

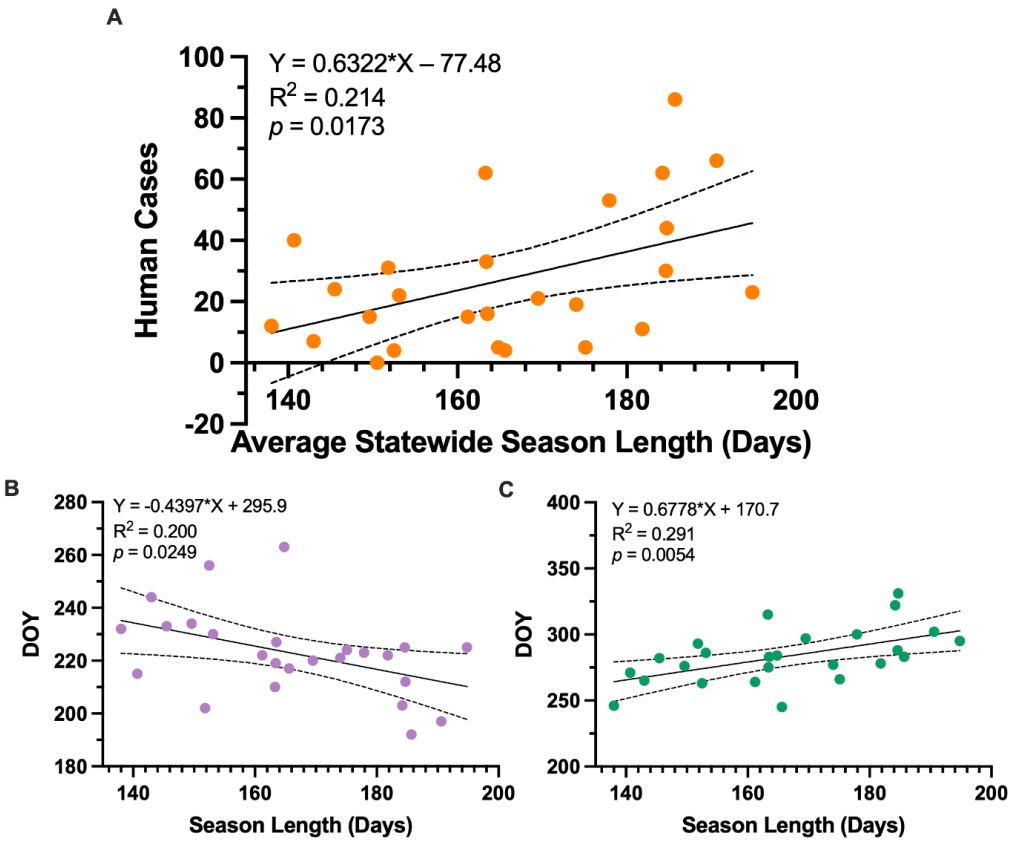

Fig 4. Human WNV cases versus season length in NYS. **A**) Total human WNV cases in New York State versus annual season length in New York State (simple linear regression *p*=0.0173). **B**) First human WNV case statewide versus annual average statewide season length (simple linear regression *p*=0.0249). **C**) Last human WNV case statewide versus annual average statewide season length (simple linear regression *p*=0.0054).

Discussion

Temperature is a known driver of vector-borne pathogen transmission, but its impact on season length has not been thoroughly investigated for most vector-borne diseases, including WNV. Here, we use county-level temperature data and the lower thermal limit for WNV transmission in *Culex pipiens* to show that the WNV transmission season length in NYS has increased by nearly 25 days, on average, from 1999 to 2024 (Fig. 1A). The extent of this transmission season increase varies by county (Fig. 1B–C) and is largest in counties with historically intermediate temperatures (Fig. 2E). We found

that the transmission season begins significantly earlier and ends significantly later, with larger changes observed for the end compared to the onset (Fig. 2). On average statewide, the last day of the season now occurs 20 days later, while the season starts 4 days earlier (Fig. 2). Examining empirical data on the timing of infection in mosquitoes and human cases suggests this change in temporal dynamics has a significant impact on WNV infection risk. Using mosquito surveillance data, we found that longer transmission seasons are associated with increased WNV prevalence (Fig. 3A). Additionally, the first positive mosquito pool is detected significantly earlier as season duration extends (Fig. 3D). Longer transmission seasons are associated with a greater number of human WNV cases, with cases occurring both earlier and later during longer seasons (Fig. 4). Together, these findings highlight the impact of climate change on the length of the WNV transmission season in NYS, extending from thermal biology to mosquito infection to human cases.

Numerous weather factors have been shown to impact WNV transmission[4,6,9,32–34]. Temperature is a major driver of the WNV transmission season length[9,18,35,36]. Studies in Europe have found that warmer springs can shape the transmission season and result in increased WNV prevalence[8,37]. In the U.S., local temperature has also been shown to dictate the seasonality of WNV transmission[18,35,36]. Our study builds on previous work by examining data spanning more than two decades to assess the relationship between extended transmission seasons and WNV prevalence in vectors and humans. Although temperature is important, it is not the only weather variable that affects WNV transmission; precipitation and humidity have also been shown to play a role[4,6,18,38]. Future work should investigate potential correlations between precipitation and humidity

with transmission season length. While many studies have investigated the impact of weather variability on WNV transmission[9,13,18,19] , this is the first to assess how climate change affects the duration of transmission and demonstrate its implications for disease spread.

Climate change continues to accelerate as mitigation efforts have so far been insufficient. Vector-borne diseases will remain sensitive to warming-driven extensions of the transmission season. These temperature increases may result in changes to thermal suitability, making certain areas more vulnerable to vector expansion[39,40], as well as providing vectors and viruses the opportunity to evolve in response to rising temperatures[41,42]. Population-specific effects of temperature are important to WNV transmission by *Culex* spp. mosquitoes[13,20], and our ability to match WNV prevalence in mosquitoes with temperature at the county level allowed us to account for such regional effects. Surprisingly, our analysis found no relationship between the last WNV-positive mosquito pool and extended transmission seasons. Although we have a robust dataset of mosquito surveillance, mosquito collection typically does not continue into late October or November. As a result, current surveillance activities are likely missing late-season transmission potential. Our study has a direct implication for surveillance and management activities, that historical sampling efforts do not fully capture expanding seasonal risk. In particular, as warming continues, effectively identifying risk will require allocation of resources to later season trapping and testing, and corresponding control efforts.

Our mosquito surveillance dataset does not include data from the five boroughs of New York City, the area where WNV transmission was initially detected in the state, and

where the largest human population resides. Although this does not bias our results, the inclusion of mosquito and human WNV prevalence data from this region could strengthen our analysis. We found a significant link between the timing of the first and last human WNV cases and the length of the transmission season. However, since reported case dates can vary with detection methods, analyzing data by detection type could reveal a stronger relationship. Additionally, while we know that avian hosts play a role in the WNV transmission cycle[43–46], we could not account for climate-driven changes in the avian community in this study due to a lack of WNV surveillance in avian populations.

This study highlights WNV as a compelling case study for understanding the influence of climate change on the seasonality of vector-borne disease transmission. Our findings demonstrate that rising temperatures have extended the WNV transmission season in NYS by nearly a month over the past 25 years, leading to earlier seasonal onset and later termination. This prolongation of the transmission window is strongly associated with increased WNV prevalence in both mosquito vectors and human cases, underscoring the tangible public health consequences that are already occurring from a warming climate. While temperature is a key driver, the complex interplay of other climatic factors, vector ecology, and host dynamics also shapes disease patterns. As climate change progresses unabated, similar shifts in thermal suitability and vector behavior are likely to facilitate the expansion and intensification of WNV and other vector-borne diseases.

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Data Availability Statement

Data was made available through the Freedom Of Information Law, Article 6 (Section 84-90), of the New York State Public officers Law, providing the public the right to access records maintained by government agencies with certain exceptions. Due to confidentiality restrictions set by the New York State Department of Health (NYSDOH), mosquito surveillance and human case data cannot be made publicly available. However, these data can be requested directly from the NYSDOH Bureau of Communicable Diseases at BCDC@health.ny.gov.

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