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Inter-Annual Associations Between Precipitation and Human Incidence of West Nile Virus in the United States

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ABSTRACT

Higher-than-average precipitation levels may cause mosquito outbreaks if mosquitoes are limited by larval habitat availability. Alternatively, recent ecological research suggests that drought events can lead to mosquito outbreaks the following year due to changes in food web structure. By either mechanism, these mosquito outbreaks may contribute to human cases of West Nile Virus (WNV) in the recent United States outbreak. Using county-level precipitation and human WNV incidence data (2002–2004), we tested the impacts of above and below-average rainfall on the prevalence of WNV in human populations both within and between years. We found evidence that human WNV incidence is most strongly associated with annual precipitation from the preceding year. Human outbreaks of WNV are preceded by above-average rainfall in the eastern United States and below-average rainfall in the western United States in the prior year. While no direct mechanism may be determined from this study, we hypothesize that differences in the ecology of mosquito vectors may be responsible for the opposite relationships between precipitation and WNV outbreaks between the eastern and western United States. Key Words: Climate—West Nile. Vector-Borne Zoonotic Dis. 7, 337–343.

INTRODUCTION

A PREVAILING DOGMA in epidemiology is that higher-than-average levels of precipitation can lead to mosquito outbreaks, which in turn cause high levels of mosquito-borne illness in humans. This pattern of a positive association with rainfall in the months preceding disease outbreaks has been demonstrated for several mosquito-borne diseases, including Ross River virus in Australia (Kelly-Hope et al. 2004), Rift Valley fever and Malaria in sub-Saharan Africa (Gerdes 2004, Thomson et al. 2006), and the recent West Nile virus (WNV) outbreak in North America (Takeda et al. 2003). Above-average precipitation could lead to a higher abundance of overwintering mosquitoes, leading to larger mosquito—and potentially disease—outbreaks, in the following year (Reiter 1988, Nasci et al. 2001). Alternatively, recent ecological research has demonstrated that droughts can facilitate population outbreaks of at least some species of mosquitoes in the following year. Chase and Knight (2003) describe this scenario as resulting from the unpredictable drying of wetlands, disrupting the aquatic food web interactions that limit larval mosquito populations.

In this study, we examined the relationship between precipitation and crude incidence rates (IRs) of WNV in humans in the United States. We investigated the importance of rainfall in the years prior to and concurrent with human IRs and whether monthly, seasonal or

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annual precipitation was the best predictor of WNV in humans. We specifically focused on the years of highest incidence (2002–2004) as WNV spread across the United States.

METHODS

For precipitation analyses, we used the Standardized Precipitation Index (SPI), which compares precipitation data for a designated period of time to historical precipitation data. Positive values indicate higher-than-normal levels of precipitation, while negative values signify lower-than-normal levels (McKee et al. 1993). Average SPI values covering a 12-month period from January through December for the year preceding and concurrent with the three years of high WNV incidence in the United States (2002–2004) were obtained from the National Agricultural Decision Support System (NADSS) databank (http://nadss.unl.edu/).

Human cases of WNV were obtained at the county level from the United States Geological Survey web page (http://westnilemaps.usgs.gov/). We obtained county-level United States census population data from a United States county shape file and calculated human IRs of WNV for all counties reporting human infections. Using geographic information systems software (ArcGIS 9.0) we merged county-level human IRs and county-level SPI values. States reporting at least 15 cases in 2002, 2003, and 2004 were included in the analysis for any year that they met this criterion. Other years (1999–2002, 2005–2006) were not included in our analyses, because few states reported 15 or more cases of WNV in these years or because the data was not available at the time the study was conducted.

For each of the 3 years, we examined the association between human IRs of WNV and SPI values from the year previous to and concurrent with the given year of WNV incidence. Analyses comprised simple linear regressions conducted in JMP software (version 5.1; SAS Institute Inc., Cary, NC). Human IRs of WNV were log-transformed to meet assumptions of normality. The analyses included all counties for which at least one human case of WNV was reported and SPI data were available (number of counties in final analyses for 2002, 619; 2003, 941; and 2004, 387).

To assess whether precipitation data for specific months provided particularly explanatory information, we further conducted the analysis described above using SPI values covering 1-month periods for each year of WNV outbreak. We repeated this analysis using monthly SPI values for each month in the year prior to WNV outbreak.

Because previous studies have found significant impacts of seasonal variation in precipitation on the prevalence of WNV (Shaman et al. 2005), we further sought to test the impact of 3-month "seasons" of precipitation on the IRs of WNV in humans. Since most human cases of WNV are reported in July, August or September (O'Leary et al. 2004), we obtained 3-month SPI values for April, May, and June and compared the importance of precipitation in these 3 months with precipitation in July, August, and September. We evaluated the influence of seasonal precipitation by correlating 3-month SPIs in the years concurrent with and preceding WNV incidence in humans.

For counties with more than one weather station, we averaged SPI values among stations. To ensure that variance among weather stations within counties was not excessively high, we calculated repeatability of SPI values using the intraclass correlation coefficient from a model II analysis of variance (ANOVA) (Lessells and Boag 1987, Sokal and Rohlf 1995) for each year of the 12-month SPI data. We found highly significant repeatability for SPI values (mean $r = 0.65$, ranging from 0.55 to 0.71; all $p < 0.0001$), confirming the validity of averaging values within counties.

Because counties geographically near one another might exhibit similar SPI and WNV values, we statistically controlled for spatial autocorrelation of data among counties. We calculated pair-wise distance matrices representing the distance between counties for each variable. Separate matrices were calculated for each analysis. A matrix of geographic distances between counties was calculated using coordinates obtained from the NADSS databank. For counties with more than one weather station, coordinates were averaged to obtain one point that was an approximation of the mid-point between stations. We then conducted partial Mantel tests in the program Passage (Rosenberg 2001) to examine whether counties with similar SPI values

exhibited similar human IRs of WNV, while controlling for spatial proximity of counties. Significance was assessed by comparing the *z*-statistic of the actual matrices to the *z*-statistics from 999 random permutations.

RESULTS

For all 3 years of high human incidence of WNV in the United States, the previous year's SPI data were more strongly correlated with human IRs of WNV than the concurrent year's SPI data (2002: $r = 0.29$ vs. $r = -0.21$; 2003: $r = -0.48$ vs. $r = -.40$; 2004: $r = -0.32$ vs. $r = -0.00$; Table 1). In 2002, human IRs of WNV were positively correlated with the previous year's precipitation (Fig. 1A and Table 1), while in 2003 and 2004 human IRs were negatively correlated with the previous year's precipitation (Fig. 1B,C and Table 1). All three results remained significant after controlling for spatial autocorrelation among counties (Table 1).

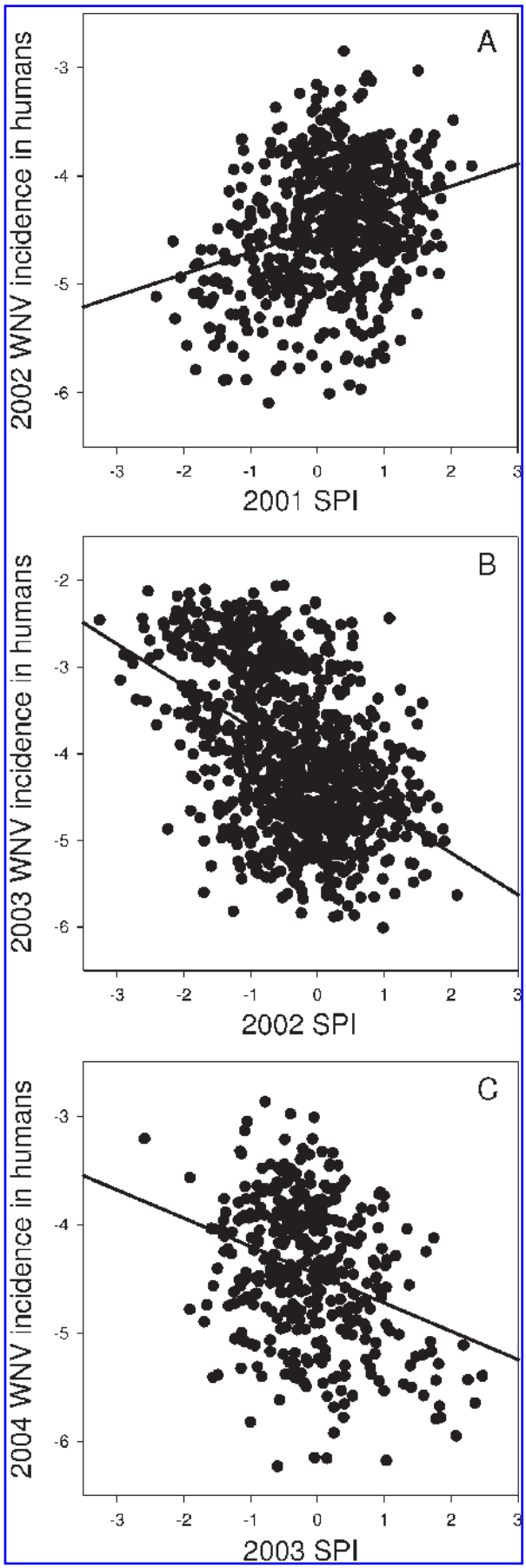
Considering the majority of human cases of WNV were located in the eastern United States in 2002 and in the western United States in 2003 and 2004, we further sought to test whether a geographic pattern might explain the opposite trends observed in 2002 versus 2003 and 2004. Using the Mississippi River as an east-west dividing line, we separately analyzed the relationship between human IRs and annual precipitation data for each region. For 2002, we found a strong positive relationship between human IRs and the previous year's precipitation in the eastern United States. In contrast, we found a strong negative relationship between human IRs and the concurrent year's precipitation in the western United States in 2002 and also between human IRs and the previous year's precipitation in the western United States in 2003 (Table 1). No other relationships within regions were significant after controlling for spatial autocorrelation among counties.

Investigation of precipitation at the monthly-scale of analysis did not reveal any specific month as particularly informative regarding WNV incidence in humans within any of the 3 years examined (Table 2). Rather, monthly SPI values exhibited a high degree of variation (in

Table 1. Relationship between West Nile Virus (WNV) Incidence in Humans and Annual Standardized Precipitation Index (SPI) Values of the Previous and Concurrent Year for Each of Three Years of WNV Data

Year of WNV	*SPI data source*	*Linear regression* P	r	*Mantel* P
2002	**2001 SPI–Overall**	<0.0001	0.29	0.038
	2001 SPI—West	0.631	0.03	—
	2001 SPI—East	<0.0001	0.41	0.001
	2002 SPI–Overall	<0.0001	−0.21	0.011
	2002 SPI—West	<0.0001	−0.32	0.002
	2002 SPI—East	0.495	−0.04	—
2003	**2002 SPI–Overall**	<0.0001	−0.48	0.001
	2002 SPI—West	<0.0001	−0.51	0.001
	2002 SPI—East	0.743	0.02	—
	2003 SPI–Overall	<0.0001	−0.40	1.0
	2003 SPI—West	<0.0001	−0.32	1.0
	2003 SPI—East	<0.0001	−0.49	0.87
2004	**2003 SPI–Overall**	0.002	−0.32	0.002
	2003 SPI—West	0.088	−0.10	0.251
	2003 SPI—East	0.002	−0.36	0.364
	2004 SPI–Overall	0.999	−0.00	—
	2004 SPI—West	0.998	−0.00	—
	2004 SPI—East	0.560	0.07	—

Mantel *p*-value represents the significance of each relationship, while statistically controlling for spatial autocorrelation of data. Boldfaced SPI data sources depict those that were significantly associated with WNV incidence in humans, after controlling for spatial autocorrelation among counties. For each year of WNV data, correlations are provided across all of the United States, as well as within western and eastern regions of the United States.



sign and magnitude), with correlations generally much weaker than annual SPI values. Similarly, no 3-month "season" in the year prior to or concurrent with the human IRs of WNV were consistently informative in predicting WNV outbreaks in humans (Table 3). Moreover, correlations were generally much weaker than annual SPI values.

DISCUSSION

In all, our results suggest that human incidence of WNV is most strongly associated with the annual precipitation of the preceding year. While we find some significant relationships between human IRs of WNV and monthly or seasonal amounts of precipitation, no consistent trend emerges from our analyses at these time scales. Interestingly, we detect a strong signal of geographic variation at the coarse scale of the eastern versus western United States. WNV was positively correlated with the previous year's precipitation in the eastern United States, which is consistent with the hypotheses that mosquito populations are limited by larval breeding habitats remaining from the previous growing season or that larger numbers of overwintering mosquitoes may initiate mosquito population outbreaks. Alternatively, in the western United States, WNV was negatively correlated with the previous year's precipitation, which is consistent with the hypothesis that mosquitoes are limited by food-web interactions, which themselves are altered by droughts (Chase and Knight 2003).

Individual monthly precipitation patterns were less informative in predicting WNV outbreaks in humans and we found no correlation with precipitation patterns in the months leading up to peak WNV incidence in humans. However, correlations between precipitation in the months immediately prior to mosquito outbreaks and human incidence of mosquito-

FIG. 1. Linear regressions examining the relationship between human crude incidence rates of West Nile virus (WNV) and the previous year's Standardized Precipitation Index (SPI) value at the county level for 2002 (**A**), 2003 (**B**), and 2004 (**C**). All regressions are significant (all $p < 0.01$), and remain significant after controlling for spatial autocorrelation among counties. Note that the *y*-axis scale is not identical for all panels of the figure.

TABLE 2. CORRELATION COEFFICIENTS (PEARSON *r*) FOR THE RELATIONSHIP BETWEEN WEST NILE VIRUS (WNV) INCIDENCE IN HUMANS AND MONTHLY STANDARDIZED PRECIPITATION INDEX (SPI) VALUES FOR THE PREVIOUS YEAR AND CONCURRENT YEAR

	2002 WNV			*2003 WNV*			*2004 WNV*		
SPI	*Overall*	*West*	*East*	*Overall*	*West*	*East*	*Overall*	*West*	*East*
Previous year									
January	0.25	0.14	0.11	−0.03	−0.09	−0.12	0.17	0.28	−0.25
February	0.18	−0.04	0.26	−0.02	−0.15	0.10	0.00	−0.02	0.03
March	−0.23	−0.21	−0.33	−0.20	−0.08	0.08	0.06	0.11	−0.35
April	0.28	0.37	0.21	−0.29	−0.32	0.01	0.14	0.12	0.09
May	0.13	0.10	0.09	−0.44	−0.34	−0.16	0.03	0.04	−0.26
June	−0.12	−0.15	−0.02	−0.36	−0.29	−0.07	0.03	0.03	−0.11
July	0.25	0.29	0.22	−0.16	−0.39	0.23	−0.36	−0.32	0.03
August	−0.05	−0.30	0.30	0.23	0.13	0.16	−0.22	−0.25	−0.17
September	−0.02	−0.04	−0.02	−0.16	0.06	0.00	−0.13	−0.01	−0.15
October	0.24	−0.05	0.47	−0.07	−0.24	0.13	−0.22	−0.07	−0.29
November	0.36	0.18	0.41	−0.35	−0.20	−0.19	−0.14	−0.03	−0.04
December	−0.06	−0.39	0.26	−0.31	−0.23	−0.16	−0.11	−0.06	−0.12
Concurrent year									
January	0.01	−0.17	0.13	0.36	0.52	−0.09	0.13	0.04	0.03
February	0.05	−0.04	0.17	−0.13	−0.17	0.01	0.09	−0.19	0.31
March	0.01	−0.06	0.19	0.18	0.30	−0.19	0.18	0.16	−0.03
April	−0.10	−0.27	0.05	0.24	0.31	0.10	0.01	−0.01	−0.26
May	−0.08	−0.18	0.15	−0.16	0.32	−0.07	0.03	0.03	0.24
June	−0.28	−0.21	−0.24	−0.13	−0.08	−0.01	0.04	0.03	0.15
July	−0.08	−0.33	0.12	−0.42	−0.25	0.11	−0.02	0.06	−0.28
August	0.13	0.19	0.02	−0.30	−0.20	−0.20	−0.23	−0.18	−0.12
September	0.00	0.06	0.11	−0.24	−0.09	−0.05	0.17	0.35	−0.19
October	0.13	0.05	0.08	−0.24	−0.04	−0.17	0.08	−0.16	0.43
November	−0.26	−0.10	−0.27	−0.16	−0.09	−0.15	0.02	−0.09	0.15
December	−0.26	−0.23	−0.24	−0.15	0.00	−0.18	−0.31	−0.27	−0.20

For each year of WNV data, correlations are provided across all of the United States, as well as within western and eastern regions of the United States.

borne disease have been found for WNV and other mosquito-borne pathogens in the United States (Takeda et al. 2003, Shaman et al. 2002, Shaman et al. 2005). It is possible that we did not detect consistent trends with precipitation in the months leading up to WNV outbreaks due to limitations of the datasets we analyzed. Monthly precipitation data may be too narrow

TABLE 3. CORRELATION COEFFICIENTS (PEARSON *r*) FOR THE RELATIONSHIP BETWEEN WEST NILE VIRUS (WNV) INCIDENCE IN HUMANS AND SEASONAL STANDARDIZED PRECIPITATION INDEX (SPI) VALUES FOR THE PREVIOUS YEAR AND CONCURRENT YEAR

	2002 WNV			*2003 WNV*			*2004 WNV*		
SPI	*Overall*	*West*	*East*	*Overall*	*West*	*East*	*Overall*	*West*	*East*
Previous year									
Jan–Mar	0.04	−0.12	0.03	−0.12†	−0.13*	0.12	0.05	0.14*	0.44*
Apr–June	0.16†	0.19*	0.04	−0.47†	−0.37†	−0.11	−0.21†	−0.06	−0.24
July–Sep	0.08	−0.06	0.33†	−0.05	−0.17†	0.20*	−0.34†	−0.21†	−0.23
Oct–Dec	0.28†	−0.09†	0.55†	−0.21†	−0.26†	0.16*	−0.31†	−0.19†	−0.41†
Concurrent year									
Jan–Mar	0.02	−0.08	0.35†	0.09*	0.25†	−0.14	0.25†	0.07	0.48†
Apr–June	−0.24†	−0.26†	−0.09	−0.08	0.30†	0.00	−0.03	−0.01	0.43†
July–Sep	0.10	−0.05	0.25†	−0.51†	−0.36†	0.14	0.12	0.33†	−0.64†
Oct–Dec	−0.03	0.02	−0.11	−0.34†	−0.12*	−0.21†	0.00	−0.12	0.62†

For each year of WNV data, correlations are provided across all of the United States, as well as within western and eastern regions of the United States.

*$p < 0.05$; †$p = 0.01$.

to detect long-term trends in precipitation events that lead to mosquito outbreaks, while still too coarse to detect specific precipitation events of high impact. Since our data do not indicate the precise month in which most WNV outbreaks occurred, it is impossible to accurately identify the month prior to WNV outbreak. Furthermore, the month of peak WNV incidence may vary from state to state.

We found some strong correlations between seasonal precipitation patterns and human IRs with WNV, although these were typically weaker than correlations observed at the annual scale. No particular season was consistently informative in predicting human cases of WNV and this may be due to the fact that the timing of seasonal trends in precipitation varies widely across the continental United States.

Due to the correlational nature of this study it is impossible to determine the mechanism behind the different trends detected in the eastern and western United States. However, one possible explanation may lie in differences in the biology of vector mosquitoes between the two regions. In the western United States, primary vectors of WNV include species such as *Culex tarsalis* (Goddard et al. 2002), a wetland-breeding mosquito that is likely to undergo outbreaks following years of low rainfall as a result of changes in food web structure. Alternatively, many of the important WNV vectors in the eastern United States (e.g., *Aedes albopictus*, *Culex pipiens*, *Culex restuans*) breed in natural and artificial containers (Turrell et al. 2005). If container breeders are less limited by predation and competition, but are instead primarily limited by habitat availability, then increased rainfall should lead to a larger population of overwintering mosquitoes by increasing the number of available larval habitats. Additionally, the bird species that serve as the primary reservoirs for WNV amplification and transmission to vector mosquitoes may vary considerably across different regions of the United States and among the myriad habitat types (e.g., urban vs. wetlands) where WNV transmission is known to occur.

Annual precipitation was a particularly superior predictor of WNV outbreaks to precipitation in any particular month or season for the western United States This is consistent with the drying of wetlands and subsequent alteration of food web patterns in the western United States, since wetlands would require several months of very low or no rainfall to completely dry. Importantly, droughts have been suggested to precede outbreaks of another mosquito-borne virus, Saint Louis Encephalitis, which has a very similar life-cycle (Day 2001, Shaman et al. 2002). Springtime drought followed by a wet summer was found to be a good predictor of WNV incidence in humans in southern Florida (Shaman et al. 2005). Hypotheses other than the disruption of food web interactions have been offered as mechanisms leading to these effects. For example, it has been argued that drought concentrates mosquitoes and reservoir hosts in remaining moist habitats, leading to increased disease transmission (Shaman et al. 2002). Alternatively, periods of drought followed by increased rainfall could facilitate disease transmission by synchronizing blood meal searches with oviposition, both of which would have been delayed by dry conditions (Provost 1969).

These proposed mechanisms are not necessarily in conflict with the long-term influence of precipitation observed in this study. Our observation of an inverse relationship with precipitation in the year preceding WNV outbreak could be due to the overall increase or decrease in mosquito populations that resulted from long-term rainfall patterns. The importance of short-term precipitation patterns observed in other studies might be focusing on the timing of mosquito breeding and biting activity that leads to WNV transmission. Some of these studies (Shaman et al. 2005) use data with higher spatial resolution that can more effectively detect these short-term trends. Therefore, it seems plausible that one could find a relationship between precipitation and WNV incidence by looking at either the long-term effects of precipitation on mosquito populations or by examining the short-term effects of precipitation on mosquito activity.

It is important to note that WNV incidence in humans is influenced by a litany of factors, including variation in temperature (Reisen et al. 2006), land use/land cover (Gibbs et al. 2006), human socioeconomics and behavior (O'Leary et al. 2004, Ruiz et al. 2002), timing of avian infection (Guptil et al. 2003) and the abundance, distribution, and identity of vector and reservoir species (Granwehr et al. 2004).

Our findings reveal that patterns of disease incidence can be influenced by long-term trends in precipitation and that the response may change over large geographic regions. Given the wide variation in species composition of mosquito vectors and avian reservoirs (www.cdc.gov/ncidod/dvbid/westnile/index.htm), it seems likely that the factors which influence transmission dynamics will change between regions. We propose that inter-annual precipitation may be one of several important factors to include in predictive models of human WNV outbreaks and mosquito control programs.

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