ARTICLE

Autism Prevalence and Precipitation Rates in California, Oregon, and Washington Counties

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Objective: To investigate empirically the possibility of an environmental trigger for autism among genetically vulnerable children that is positively associated with precipitation.

Design: We used regression analysis to investigate autism prevalence rates and counts first in relation to mean annual county-level precipitation and then to the amount of precipitation a birth cohort was exposed to when younger than 3 years, controlling for time trend, population size, per capita income, and demographic characteristics. In some models, we included county fixed-effects rather than a full set of covariates.

Setting: Counties in California, Oregon, and Washington.

Participants: Children born in California, Oregon, and Washington between 1987 and 1999.

Main Exposure: County-level precipitation.

Main Outcome Measures: County-level autism prevalence rates and counts.

Results: County-level autism prevalence rates and counts among school-aged children were positively associated with a county's mean annual precipitation. Also, the amount of precipitation a birth cohort was exposed to when younger than 3 years was positively associated with subsequent autism prevalence rates and counts in Oregon counties and California counties with a regional developmental services center.

Conclusions: These results are consistent with the existence of an environmental trigger for autism among genetically vulnerable children that is positively associated with precipitation. Further studies focused on establishing whether such a trigger exists and identifying the specific trigger are warranted.

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THIRTY YEARS AGO, IT WAS estimated that roughly 1 in 2500 children had autism; the most recent Centers for Disease Control and Prevention (CDC) study calculated prevalence at 1 in 150.[1] Some of this increase is likely owing to more active case ascertainment and changes in diagnostic criteria, and as much as half of the prevalence variation between studies is owing to differences in methods and population characteristics.[2,3] Nevertheless, the possibility of a true increase in prevalence cannot be excluded.[4]

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Despite the increase in prevalence and the resulting increased attention paid to the condition, knowledge about what causes autism is limited. It is understood that biological factors play an important role, but environmental triggers may also be important. However, little is known about what these triggers might be. We explore the possibility of an environmental trigger for autism by empirically investigating the association between county-level precipitation rates and the prevalence of autism.

The US Department of Education collects autism prevalence data by state. According to the 2003 survey, the 5 states with the lowest autism prevalence for 6- to 10-year-olds were New Mexico, Mississippi, Colorado, Oklahoma, and Tennessee, whereas Minnesota, Oregon, Indiana, Maine, and Massachusetts had the highest autism prevalence for this age group.[5] Similarly, in the recent CDC study of autism prevalence mentioned previously, the highest autism prevalence among the 14 states studied was found in New Jersey, the second–most-northern state in the study, whereas the lowest autism prevalence was found in Alabama, the most southern state in the study.[1]

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This pattern suggests a hypothesis: namely, that there is an environmental trigger for autism among genetically vulnerable children that is correlated with bad weather, possibly because the environmental trigger is associated with indoor activities. We explore this hypothesis by empirically investigating the association between autism prevalence and precipitation rates.

METHODS

DATA

We focused on data from 3 states: California, Oregon, and Washington. Two of our tests required high precipitation variability across counties. The Cascade Mountains run north to south across Oregon and Washington, and, in both states, western counties experience almost 4 times more precipitation than eastern counties. We also included California because it has been the focus of numerous past studies of autism rates and has relatively high precipitation variability across counties.

State agencies in Oregon and Washington report the number of children aged 6 to 18 years in December 2005 who were diagnosed with autism, by county of residence. The California Department of Developmental Services reports the number of children diagnosed with autism receiving services at one of California's 21 regional centers, again by county of residence. The autism prevalence for school-aged children is calculated by dividing the number of 6- to 18-year-olds with autism in a county by the corresponding county-level school-aged population, as reported in the 2000 US Census.

We also calculated county-level age-specific autism prevalence. Washington did not provide these data, whereas Oregon provided figures when a county's age-specific count was at least 10. For Oregon, we used age-specific counts in 2005 to construct an autism prevalence rate for each of 13 cohorts born from 1987 through 1999 by dividing by the corresponding county-level age-specific population. For California, we focused on the same cohorts but used the county autism prevalence count in the year a birth cohort was 8 years old (for the 1998 birth cohort, we used the autism prevalence count of 7-year-olds in 2005, and for the 1999 cohort, we used the 2005 count of 6-year-olds) and constructed the autism prevalence rate by dividing by the corresponding county-level age-specific population. California's data construction procedure should have less measurement error because some children with autism may have changed county of residence between age 3 years and when they were recorded in the data sets. Unfortunately, data limitations prevented us from using this procedure for Oregon.

In our tests, we used a relative precipitation variable, which we defined as the difference between the annual precipitation received in a county and the mean precipitation for all counties in the sample. The National Climatic Data Center records daily precipitation at more than 8000 weather stations in the United States. To calculate precipitation in a specific county in a specific year, we first calculated the mean across all weather stations in the county for each day of the year. We added the resulting values from all the days in the year to get the total precipitation, and then calculated mean annual precipitation by county from 1987 through 2001 and for each 3-year interval when the 1987 through 1999 birth cohorts were younger than 3 years. To find relative precipitation levels, we then subtracted the mean annual precipitation level for the counties and years in our sample. The 1987-2001 period spans the dates when children who were school aged in 2005 were younger than 3 years, the time during which autism symptoms emerge and any putative, postnatal factor would be present.[6]

We also included various covariates: a county's total population, per capita income, and the percentage of the population who were Hispanic, black, or members of an indigenous group (American Indians or Alaskan natives). To calculate these percentages, we used population data by group and age range taken from the US Census.

This study was approved by the Cornell University Institutional Review Board.

ANALYSIS

We focused on whether autism prevalence was higher in counties that received relatively high precipitation, and whether this relationship was also true for birth cohorts in a county that experienced heavy precipitation, relative to that county's mean, when the cohort was younger than 3 years. Using ordinary least squares regression, we analyzed the county-level autism prevalence in 2005 for children aged 6 through 18 years in California, Oregon, and Washington in relation to the mean annual precipitation rate in that county from 1987 through 2001 and county-level demographic covariates. Separately, we analyzed the autism prevalence rate for each birth cohort in California and Oregon counties from 1987 through 1999 in relation to the mean annual precipitation rates in those counties when the cohort was younger than 3 years. We clustered the standard errors to allow the error terms to be correlated within a county over time.

One concern with this approach was that families predisposed to having autistic children may, for one reason or another, have been located disproportionately in counties that received substantial precipitation. We addressed this concern in 2 ways. First, we controlled for the per capita income and racial/ethnic mix of each county. Second, we used a county fixed-effects regression that controlled for county variables (measured and unmeasured) that did not change during the sample period. The fixed-effects regression analysis tested whether birth cohorts that were exposed to a large amount of precipitation, relative to the county mean, when younger than 3 years, had a higher autism prevalence rate relative to the county mean.

A second concern is whether results were driven by the rising prevalence of autism over time. To address this issue, we included linear, squared, and cubed time trend variables to allow for a flexible trend in diagnoses over time, independent of changes in precipitation.

Another concern was that some California counties did not have a regional developmental services center, which likely means a smaller proportion of children diagnosed with autism who were originally born in those counties were recorded in our data as eventually residing in those counties. This may occur because some families with autistic children born in counties without a regional center may have moved to counties with such a center (because regional centers provide services) and some families who did not move may never have registered at a regional center because of the distance to the nearest center.

We accounted for this potential problem in 2 ways. First, we included in the regressions an indicator variable for California counties with a regional center. Second, a number of our tests considered how a cohort's exposure to precipitation levels while younger than 3 years was associated with subsequent prevalence. Because an unknown and likely varying number of each cohort's autistic children born in California counties without a regional center were not included in our data as residing in that county, any measured effect of precipitation on autism prevalence in those counties was likely to be substantially smaller. Therefore, in the relevant regression analyses, we allowed precipitation to have a separate effect in California coun-

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ties without a regional center and all other counties and focused on the precipitation coefficient for the counties in Oregon and the California counties with a regional center where the coefficient should have been larger.

Finally, we performed 2 additional analyses to verify that the results were robust. First, because the population of school-aged children differed substantially among counties, the prevalence of autism was likely to be estimated more precisely in relatively populous counties, which can cause the standard errors in ordinary least squares regression to be incorrect. To address this concern, we repeated the analyses using negative binomial regression in which the dependent variable was the number of children in a county diagnosed with autism in 2005 rather than the autism prevalence rate. In the negative binomial regressions, the coefficient on the logarithm of a county's population was constrained to be 1. Second, we addressed the possibility that the error terms in the ordinary least squares regression between adjacent counties may have been correlated by correcting the standard errors for spatial dependence.[7]

RESULTS

As mentioned in the "Methods" section, the Cascade Mountains run north to south across Oregon and Washington and create 2 vastly different precipitation patterns. Counties west of the Cascades receive almost 4 times more precipitation, on average, than eastern counties (**Figure 1** and **Figure 2**). As indicated in Figures 1 and 2, in December 2005, autism rates for school-aged children were much higher in the western counties. There was less precipitation variation between counties in California (**Figure 3**), and the direct relationship between precipitation and autism was weaker there than for Oregon and Washington.

Table 1 reports coefficient estimates from the first precipitation regression. The dependent variable was the 2005 autism prevalence rate among school-aged children in a particular county of California, Oregon, or Washington, measured as a percentage. After controlling for differences in population size, demographic characteristics, per capita income, state, and whether a California county had a regional developmental services center, the coefficient for the mean annual precipitation received by a county between 1987 and 2001 was positive and significant (0.0034; 95% confidence interval [CI], 0.0018-0.0050). The coefficients for the control variables indicated that the prevalence of autism was higher in populous counties (0.026; 95% CI, 0.001-0.051) and lower in counties with a relatively high indigenous group population (–0.0080; 95% CI, –0.013 to –0.0032). Relative to California, the prevalence of autism was similar in Washington and higher in Oregon (0.46; 95% CI, 0.37-0.55) after controlling for other county characteristics.

In **Table 2** we performed this analysis again using a negative binomial regression in which the dependent variable was the number of school-aged children in a county diagnosed with autism in 2005 rather than the autism prevalence rate. Note that with a negative binomial regression, incidence-rate ratios higher than 1 are analogous to positive coefficients in an ordinary least squares regression, whereas incidence-rate ratios less than 1 are analogous to negative coefficients. Qualitatively, the results in Table 2 are similar to those in Table 1; most important, the incidence-rate ratio for mean annual precipitation is higher than 1 and statistically significant (1.007; 95% CI, 1.003-1.011). The only difference between the tables is that in Table 2 the incidence-rate ratio for being in a Washington county was statistically significant (1.39; 95% CI, 1.14-1.70), and, similarly, the incidence-rate ratio for being in a California county with a regional center was also statistically significant (1.34; 95% CI, 1.08-1.65).

In **Table 3** we focus on county autism prevalence rates by birth cohort in California and Oregon. Model 1 included a full set of covariates. The coefficient on mean annual precipitation when the cohort was younger than 3 years was positive and significant in Oregon and California counties with a regional center (0.0079; 95% CI, 0.0021-0.0137) and positive and insignificant in California counties without a regional center. The mean prevalence of autism was higher in Oregon counties (0.613; 95% CI, 0.479-0.747) and higher in California counties with a regional center (0.087; 95% CI, 0.0010-0.174). Model 2 included county fixed-effects rather than a full set of county-level covariates. As before, the coefficient for mean annual precipitation when the cohort was younger than 3 years was positive and significant in Oregon counties and California counties with a regional center (0.0057; 95% CI, 0.0021-0.0093) and insignificant in California counties without a regional center.

In **Table 4** we performed this analysis again using a negative binomial regression in which the dependent variable was autism counts by birth cohort in California and Oregon counties. As was true before, using a negative binomial regression rather than an ordinary least squares regression did not change the qualitative nature of the results.

Finally, for each of the 3 ordinary least squares regression analyses, we conducted a procedure that addressed the possibility that the error terms between adjacent counties may be correlated. The specific procedure we used left estimated coefficients unchanged but estimated standard errors corrected for spatial dependence between contiguous counties. The new standard errors for the main precipitation coefficients were 69% to 80% smaller than those reported in Tables 1 and 3, so these coefficients remain statistically significant at the 1% level.

COMMENT

This study empirically examines the hypothesis that there is an environmental trigger for autism among genetically vulnerable children that is positively associated with precipitation. If there is such an environmental trigger, then the prevalence of autism should be higher in counties that receive abundant precipitation, and especially for birth cohorts that receive above-average precipitation, relative to the county's average amount, when the cohort was younger than 3 years.

Our results support this hypothesis. Autism prevalence rates for school-aged children in California, Oregon, and Washington in 2005 were positively related

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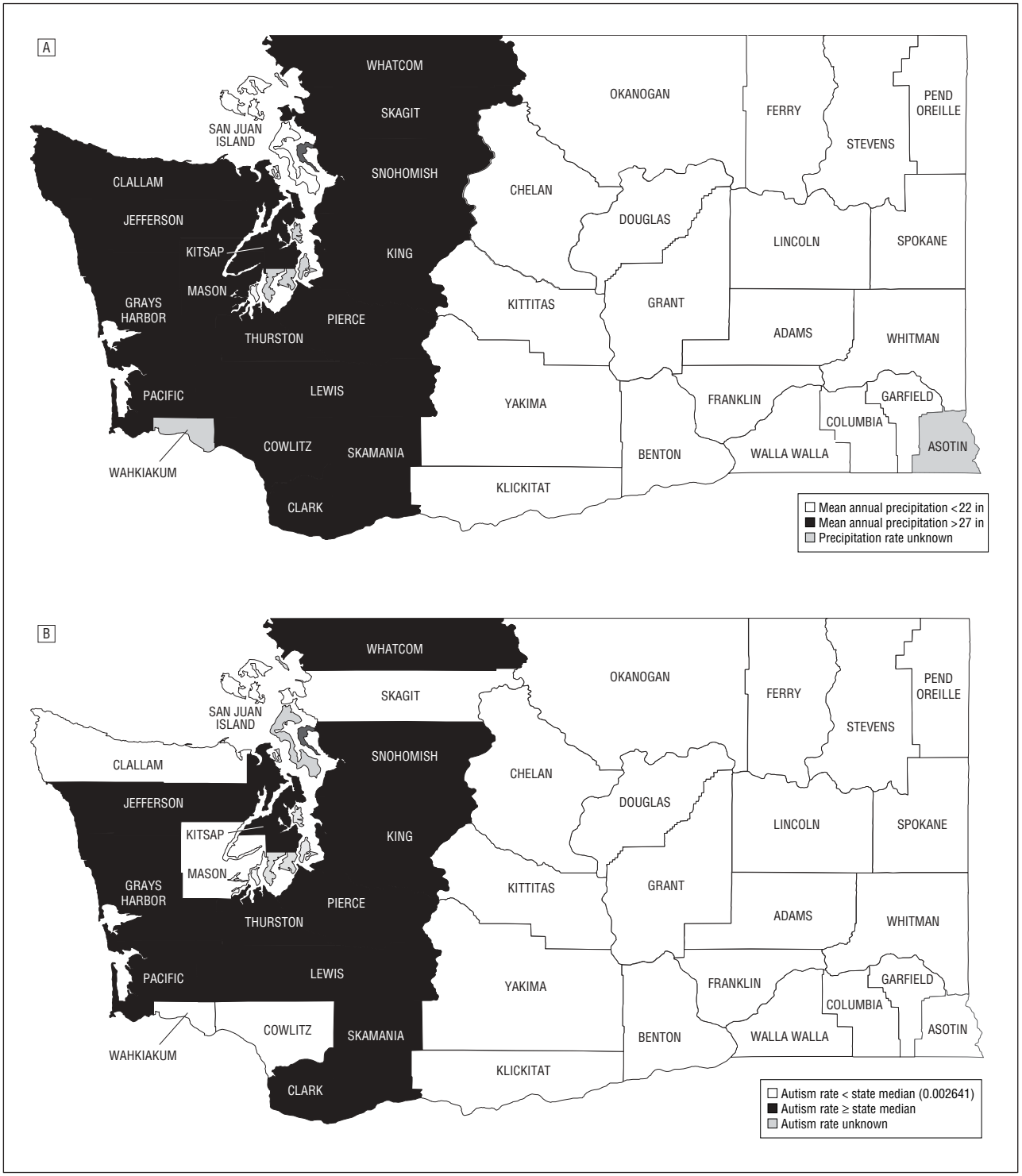


Figure 1. Precipitation (A) (1987-2001) and autism rates (B) (2005) for Washington counties. Autism prevalence rates are for children aged 6 through 18 years. Precipitation was measured from July 1, 1987, through June 30, 2001.

to the amount of precipitation these counties received from 1987 through 2001. Similarly, focusing on Oregon and California counties with a regional center, autism prevalence was higher for birth cohorts that experienced relatively heavy precipitation when they were younger than 3 years.

The magnitude of the measured relationships is substantial. For the following calculation, let us suppose that our results are indeed owing to the existence of an environmental trigger for autism. We can then estimate how much lower autism prevalence rates would be if all the increased exposure of genetically vulnerable children to this environmental trigger correlated with precipitation were eliminated. Multiplying the coefficient from the precipitation variable in Table 3 (0.0057) by the sample mean annual precipitation amount (35.6

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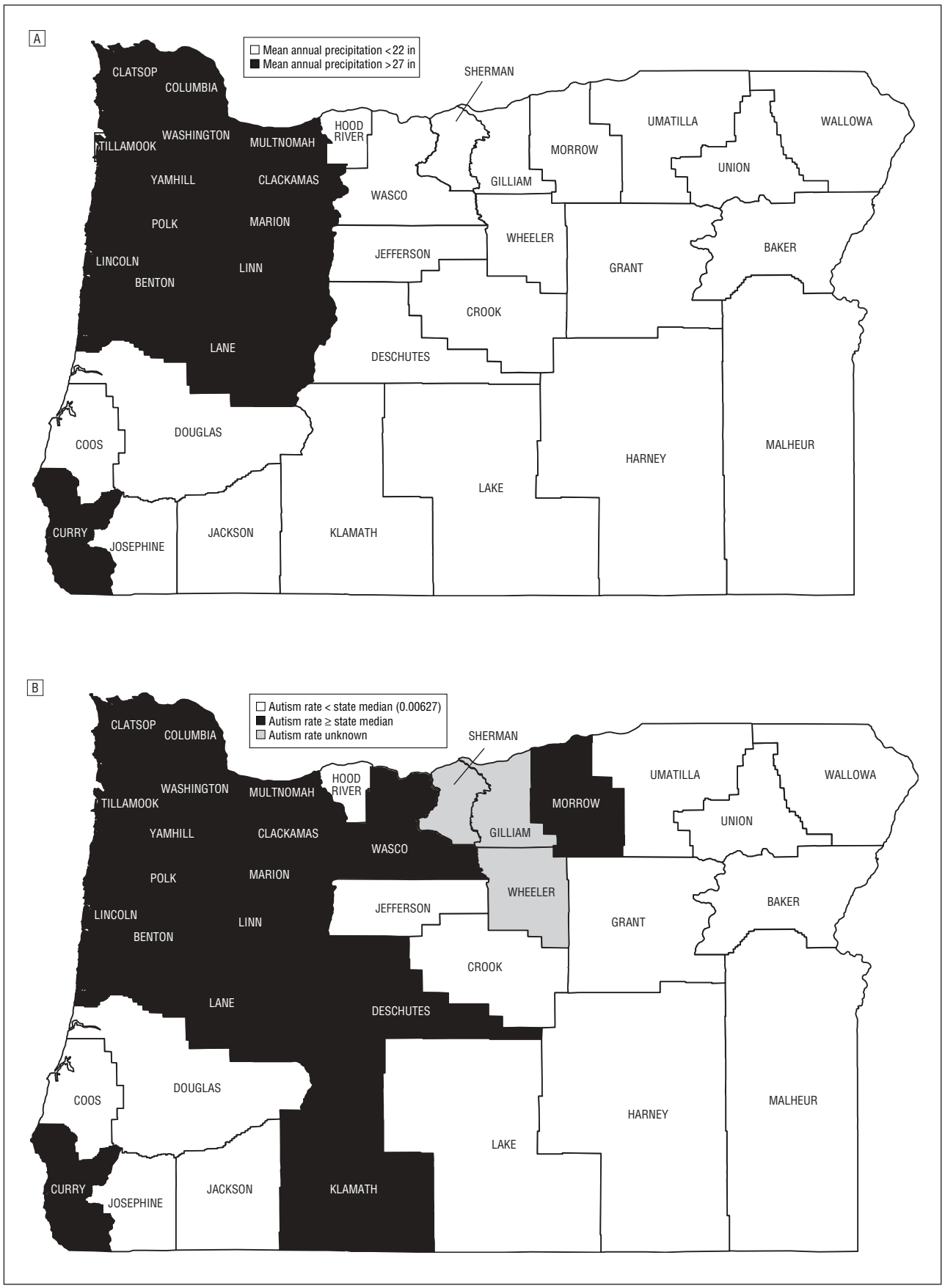


Figure 2. Precipitation (A) (1987-2001) and autism rates (B) (2005) for Oregon counties. Autism prevalence rates are for children aged 6 through 18 years. Precipitation was measured from July 1, 1987, through June 30, 2001.

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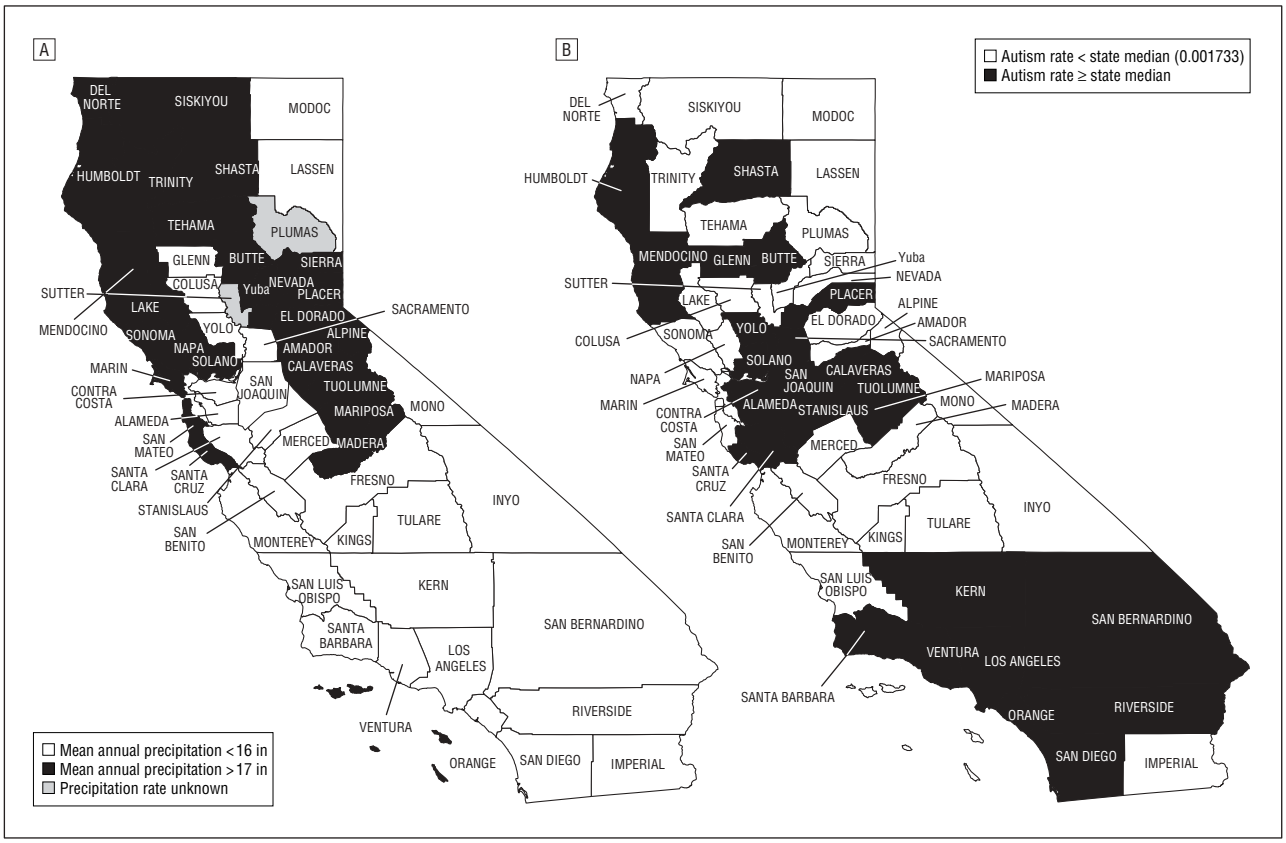


Figure 3. Precipitation (A) (1987-2001) and autism rates (B) (2005) for California counties. Autism prevalence rates are for children aged 6 through 18 years. Precipitation was measured from July 1, 1987, through June 30, 2001.

Table 1. County-Specific Autism Prevalence and Mean Precipitation Using Ordinary Least Squares Regression

Variable	Coefficient (95% Confidence Interval)
Mean annual precipitation in inches, 1987-2001	0.0034 (0.0018 to –0.0050)[a]
Logarithm of county population	0.026 (0.001 to 0.051)[b]
County per capita income, $	–0.0039 (–0.0079 to 0.0002)
Ethnicity, % of 6- to 18-year-olds in the county	
Hispanic	–0.00043 (–0.0023 to 0.0014)
Black	0.00017 (–0.0050 to 0.0053)
American Indian or Alaska native	–0.0080 (–0.013 to –0.0032)[a]
Indicator of whether a county is located in Oregon	0.461 (0.37 to 0.55)[a]
Indicator of whether a county is located in Washington	0.042 (–0.0069 to 0.092)
Indicator of whether a California county has a regional center	0.030 (–0.016 to 0.076)
Constant	–0.0080 (–0.245 to 0.229)
No. of observations	119
R^2	0.77

[a] $P < .01$.
[b] $P < .05$.

Table 2. County-Specific Autism Counts and Mean Precipitation Using Negative Binomial Regression[a]

Variable	Incidence-Rate Ratios (95% Confidence Interval)
Mean annual precipitation in inches, 1987-2001	1.007 (1.003-1.011)[b]
County per capita income, $	0.994 (0.978-1.010)
Ethnicity, % of 6- to 18-year-olds in the county	
Hispanic	0.997 (0.991-1.002)
Black	1.015 (0.992-1.038)
American Indian or Alaska native	0.954 (0.929-0.979)[b]
Indicator of whether a county is located in Oregon	3.72 (3.03-4.58)[b]
Indicator of whether a county is located in Washington	1.39 (1.14-1.70)[b]
Indicator of whether a California county has a regional center	1.34 (1.08-1.65)[b]
Observations	119

[a] The coefficient on the logarithm of a county's school-aged population is constrained to be 1.
[b] $P < .01$.

inches) yields a rate of 0.203, which represents approximately 43% of the mean 2005 school-aged autism prevalence rate for Oregon and California counties with a regional center. A similar calculation using the results of the negative binomial regression (Table 4) yields an estimated reduction of 33% of the mean 2005 school-aged autism prevalence rate for Oregon and California counties with a regional center.

There are a number of possibilities concerning what such an environmental trigger might be. One possibility is early

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Table 3. County-Specific Autism Prevalence by Birth Cohort in California and Oregon and Mean Precipitation When Birth Cohort Was Younger Than 3 Years Using Ordinary Least Squares Regression

Variable	Coefficient (95% Confidence Interval)	
	Model 1	Model 2[a]
Precipitation when cohort was aged 0-2 years	0.0079 (0.0021-0.0137)[b]	0.0057 (0.0021 to 0.0093)[b]
Precipitation when cohort was in California counties without a regional center	0.0004 (–0.0011 to 0.0019)	–0.0008 (–0.0031 to 0.0015)
Logarithm of population	0.0064 (–0.024 to 0.037)	Not applicable
Per capita income, $	–0.0029 (–0.0066 to 0.0001)	Not applicable
Ethnicity, % of 6- to 18-year-olds in the county		
Hispanic	0.0008 (–0.114 to 0.267)	Not applicable
Black	0.0025 (–0.0042 to 0.0093)	Not applicable
Indigenous groups	–0.0081 (–0.020 to 0.0040)	Not applicable
Time trend	0.041 (0.017 to 0.065)[b]	0.040 (0.020 to 0.061)[b]
Time trend, squared	–0.0043 (–0.0095 to 0.0010)	–0.0040 (–0.0086 to 0.0007)
Time trend, cubed	0.0002 (–0.0001 to 0.0005)	0.0002 (–0.0001 to 0.0005)
Indicator of whether a California county has a regional center	0.087 (0.0010 to 0.174)[c]	Not applicable
Indicator of whether a county is located in Oregon	0.613 (0.479 to 0.747)[b]	Not applicable
Constant	–0.026 (–0.393 to 0.340)	0.057 (–0.0087 to 0.122)
Observations	824	824
R^2	0.67	0.75

[a] Includes county fixed effects.
[b] $P < .01$.
[c] $P < .05$.

Table 4. County-Specific Autism Counts by Birth Cohort in California and Oregon and Mean Precipitation When Birth Cohort Was Younger Than 3 Years Using Negative Binomial Regression[a]

Variable	Incidence-Rate Ratios (95% Confidence Interval)	
	Model 1	Model 2[b]
Precipitation when cohort was aged 0-2 years		
Oregon counties and California counties with a regional center	1.008 (1.003-1.013)[c]	1.010 (1.005-1.014)[c]
California counties without a regional center	1.003 (0.993-1.013)	1.001 (0.995-1.007)
Per capita income, $	1.009 (0.987-1.031)	Not applicable
Hispanic, %	1.006 (0.996-1.016)	Not applicable
Black, %	1.007 (0.989-1.025)	Not applicable
Indigenous groups, %	0.983 (0.927-1.042)	Not applicable
Time trend	1.37 (1.28-1.47)[c]	1.39 (1.29-1.49)[c]
Time trend, squared	0.978 (0.964-0.992)[c]	0.983 (0.970-0.995)[c]
Time trend, cubed	1.001 (1.000-1.002)	1.000 (1.000-1.001)
Indicator of whether a California county has a regional center	1.30 (1.07-1.58)[c]	Not applicable
Indicator of whether a county is located in Oregon	6.32 (4.89-8.16)[c]	Not applicable
Observations	824	824

[a] The coefficient on the logarithm of a county's school-aged population is constrained to be 1.
[b] Includes county fixed effects.
[c] $P < .01$.

childhood television and video viewing.[8-13] It seems plausible that early childhood television and video viewing is positively associated with precipitation. Furthermore, television and video viewing by very young children has previously been associated with psychopathological characteristics in the pediatric literature,[14-17] including problems concerning language development,[18-20] cognitive development,[21] and the development of later behaviors consistent with attention-deficit hyperactivity disorder.[22] So one possibility is that early childhood television and video viewing by typical children is associated with various mild negative health consequences, whereas in a genetically vulnerable population it is associated with more serious health problems such as autism.

Another possibility is that vitamin D deficiency is an environmental trigger for autism.[23] Because precipitation very likely leads to less time outdoors and sunshine is the major source of vitamin D, precipitation is plausibly associated with a higher frequency of vitamin D deficiency. Vitamin D deficiency can lead to reduced levels in the developing brain of calcitriol, a critical neurosteroid involved in brain development. Of interest, while health care providers have exhorted patients during the last 20 years to reduce sunshine exposure, autism prevalence has been increasing. It is also of interest to note that evidence indicates a substantial incidence of vitamin D deficiency in the United States and elsewhere among infants and toddlers.[24]

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More generally, because young children likely spend more time indoors on high precipitation days, our results could potentially be explained by any environmental trigger associated with indoor activities. For example, a chemical used in household cleaners may serve as a trigger, and precipitation, with the concomitantly increased time that children spend indoors, may indirectly increase exposure to this chemical. Studies have found that environmental agents such as certain types of air pollution may serve as environmental triggers for autism,[25,26] but no previous study has presented statistical evidence of an environmental trigger specifically associated with indoor activities. Notably, the ongoing CHARGE (Childhood Autism Risks from Genetics and Environment) Study[27] will examine a number of chemical and biological exposures in the origins of autism.

Finally, there is also the possibility that precipitation itself is more directly involved. For example, there may be a chemical or chemicals in the upper atmosphere that are transported to the surface by precipitation. Our results could be explained by one of these chemicals being an environmental trigger for autism because precipitation would increase the prevalence of the chemical on the ground and therefore potentially increase the exposure rate with genetically vulnerable children. Another possibility is that increased precipitation might promote weed growth or expansion of the insect population, which triggers an increased use of pesticides, which may serve as an environmental trigger for autism. In fact, there is some evidence that certain pesticides are an environmental trigger for autism.[28]

There are several potential concerns with our approach. One is that families more prone to having autistic children may reside in areas with high levels of precipitation, or that such areas might use broader diagnostic criteria for diagnosing autism. However, the results persisted when we used county-level fixed-effects regression, which controlled for unmeasured time invariant county variables. This makes it unlikely that differences between counties in family characteristics and diagnostic criteria explain the results.

A second potential concern to be aware of is reverse causality. However, the methods we used eliminate this as a serious concern. Clearly, there is no meaningful sense in which the presence of a high number of young children in a county's birth cohort prone to autism "causes" precipitation to increase in that county.

It is also likely that state agency/school definitions of autism vary among states and counties and even over time within a state or county.[29,30] Nevertheless, it is unlikely that such variations would create the relationships between precipitation and autism that we find. For example, although it is theoretically possible that a county adopts conservative autism diagnostic criteria for cohorts who experienced little precipitation when young and generous diagnostic criteria for cohorts who experienced significant precipitation, this seems unlikely. Another concern is that some children moved across counties between the time of their birth and when they were recorded in our data. However, such measurement error would bias coefficients toward 0 and therefore would bias against finding statistically significant results.

Because we do not provide direct clinical evidence of an environmental trigger for autism among genetically vulnerable children that is positively associated with precipitation, our results are clearly not definitive evidence in favor of the hypothesis. But the results are consistent with the hypothesis, and, therefore, further research focused on establishing whether such a trigger exists and on identifying it is warranted.

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Announcement

Trial Registration Required. In concert with the International Committee of Medical Journal Editors (ICMJE), *Archives of Pediatrics and Adolescent Medicine* will require, as a condition of consideration for publication, registration of all trials in a public trials registry (such as http://ClinicalTrials.gov). Trials must be registered at or before the onset of patient enrollment. This policy applies to any clinical trial starting enrollment after July 1, 2005. For trials that began enrollment before this date, registration will be required by September 13, 2005, before considering the trial for publication. The trial registration number should be supplied at the time of submission.

For details about this new policy, and for information on how the ICMJE defines a clinical trial, see the editorials by DeAngelis et al in the September 8, 2004 (2004; 292:1363-1364) and June 15, 2005 (2005;293:2927-2929) issues of *JAMA*. Also see the Instructions to Authors on our Web site: www.archpediatrics.com.

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