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Spatial patterns of precipitation quantity and chemistry and air temperature in the Adirondack region of New York

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Abstract

Regional assessments are critical to evaluate resources at risk from disturbances, such as acidic deposition, which occur in large spatial extent. It is imperative to accurately quantify atmospheric deposition to the regions like the Adirondack Mountains of New York where soils and surface waters are highly sensitive to inputs of strong acids. Spatial patterns in precipitation quantity and concentrations of major ions in precipitation in the Adirondack region were estimated based on the locations of monitoring sites using the data from 1988 to 1999. Mean monthly minimum and maximum daily air temperatures were also predicted to characterize site conditions. The trends in precipitation quantity, temperature, and most ion concentrations during the period examined were not significant or minimally significant, suggesting that the mean values over the period could be used for the regression models to describe spatial patterns. The spatial variations in the mean annual and monthly precipitation amounts, monthly mean minimum and maximum daily temperatures, and annual and quarterly sulfate and nitrate concentrations were generally explained by the regression models. Comparisons with the regression models of Ollinger et al. (US Ecological Applications 3(3) (1993) 459; US Department of Agriculture, Forest Service, Radnor, PA., 1995, 30p.) for the northeastern US suggest local variations in climate variables for the smaller Adirondack region. Further, precipitation quantity, minimum and maximum temperatures, and concentrations and deposition of ions in precipitation were predicted for the entire Adirondack region, using digital elevation models among others. Precipitation quantity and the sulfate and nitrate concentrations generally increased from the northeast to the southwest. Precipitation quantity and sulfate concentrations also generally increased with elevation. Minimum and maximum temperatures decreased from the southeast to the northwest and with elevation. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Surface waters in the northeastern United States are sensitive to inputs of strong acid as defined by an acid neutralizing capacity (ANC) $< 50 \mu\text{eq l}^{-1}$ (Driscoll et al., 2001). A synoptic survey of lakes in the Adirondack region of New York State, conducted in the mid 1980s,

showed that 26% of the 1469 lakes surveyed with the surface area > 0.5 ha had negative ANC values (Kretser et al., 1989), suggesting high sensitivity to acidic deposition. Atmospheric emissions of chemicals have changed over the past 30 yr as a result of air pollution control legislation. The emissions of sulfur dioxide (SO_2) have decreased since 1973 after the 1970 Amendments to the Clean Air Act, while emissions of nitrogen oxide (NO_x) have remained essentially unchanged since 1980 (Driscoll et al., 2001). Acidic deposition to sensitive ecosystems may result in the acidification of soils,

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increases in the susceptibility of trees to insect or climate stress, and the acidification of surface waters, causing decreases in species richness of aquatic biota (Driscoll et al., 2001). Studies of the response of lake–watershed ecosystems to acidic deposition require accurate determinations of the magnitude and temporal changes in atmospheric deposition.

Methods for estimating precipitation quantity from point data include, among others: (a) regression analysis using geographic position and elevation as independent variables (Ollinger et al., 1993, 1995); (b) interpolation procedures, such as kriging, a geostatistical approach (e.g., Dingman et al., 1988); and (c) the use of digital elevation models and other orographic models for representing topographic effects on climate variables (e.g., Peck and Schaake, 1990) or a combination of physical and numerical approaches (e.g., Daly et al., 1994). Atmospheric sulfur deposition has also been estimated by a high-resolution geographic information system distributed model (Miller, 2000). Spatial interpolation methods and physical approaches require results to be stored in a digital form. Ollinger et al. (1995) indicated that regression methods have the advantage that simple equations for predicting spatial patterns can be readily incorporated into ecological models. The regression models of Ollinger et al. (1993, 1995) were developed for the northeastern United States from western New York State and Pennsylvania to Maine to capture the spatial patterns of atmospheric deposition across the entire region.

The concentrations of chemical species in precipitation have been thought to be relatively uniform across the Adirondacks with wet deposition being largely a function of precipitation quantity (Driscoll et al., 1991). Since both regional climatic patterns and local topographical variability constitute spatial trends in climatic variables, precipitation amounts and chemistry could vary across the Adirondack region that comprises local topographic variations. The data from the New York State Atmospheric Deposition Monitoring Network (NYS-ADMN) of Department of Environmental Conservation, together with the data of the National Atmospheric Deposition Program/National Trends Network (NADP/NTN), which included two sites in the Adirondack Park, and the National Climate Data Center (NCDC), provided an opportunity to evaluate spatial patterns of precipitation quantity and chemistry across the Adirondacks.

The objectives of this analysis were to develop empirical models to predict precipitation quantity, concentrations of chemical species in precipitation, and monthly minimum and maximum daily air temperatures across the Adirondacks and to characterize regional deposition patterns from 1988 to 1999. The analysis of ion concentrations in wet deposition included sulfate (SO_4^{2-}) and nitrate (NO_3^-), ammonium (NH_4^+), calcium

(Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+), chloride (Cl^-), and hydrogen ion (H^+).

2. Methods

2.1. Data used in the analyses

Annual and monthly precipitation and monthly minimum and maximum temperatures were obtained from the NCDC. Among the NCDC monitoring sites inside and near the Adirondack Park, the sites that had measured values from 1988 to 1999 with missing values of no more than 2 yr were selected for this analysis. The data from 24 monitoring sites for precipitation and those from 15 sites for minimum and maximum temperatures (Fig. 1; Table 1) were then used for developing regression models, using longitude, latitude, and elevation as independent variables.

The annual and quarterly data of the concentrations of SO_4^{2-} , NO_3^- , NH_4^+ , H^+ , Ca^{2+} , Mg^{2+} , K^+ , Na^+ , and Cl^- from 1988 at four monitoring sites (Whiteface Mountain B (WF-B), Piseco Lake (Piseco-L), Nicks Lake Campground (Nicks), and Wanakena Ranger School B (WRS-B)) were obtained from the NYS-ADMN (Fig. 1, Table 1). The annual and monthly data from the Huntington Wildlife Forest (HWF) and Whiteface Mountain A (WF-A) were obtained from the NADP/NTN (Fig. 1, Table 1). The concentrations of hydrogen ion (H^+) were calculated from the pH values. Quarterly precipitation-weighted ion concentrations for the NADP sites were calculated from their monthly precipitation and ion concentrations to make these data comparable with the quarterly data reported for the NYS-ADMN.

The quality of the ion concentration data was first assessed by visual examination of time-series plots from 1988 to 1999 and the application of analysis of variance for the examination of the differences in the concentrations among the sites, using protected least significant difference for mean separation at the 5% level. The charge balances and the regression analyses of the H^+ concentrations as a function of the sum of SO_4^{2-} and NO_3^- concentrations were then conducted to assess the accuracy of precipitation chemistry at individual sites. The magnitude and temporal variations in the SO_4^{2-} and NO_3^- concentrations were relatively consistent among the six sites. Consistency and similarity in the magnitude and temporal variations in these ion concentrations at the neighboring WF-A and WF-B sites suggested the usefulness of these ion concentration data at the NYS-ADMN sites. The regressions of H^+ against the sum of NO_3^- and SO_4^{2-} for the NADP sites had $R^2 > 0.91$. These relationships were weaker, however, for the NYS-ADMN sites (R^2 from 0.44 to 0.69), suggesting that the pH values of the NYS-ADMN sites should not be

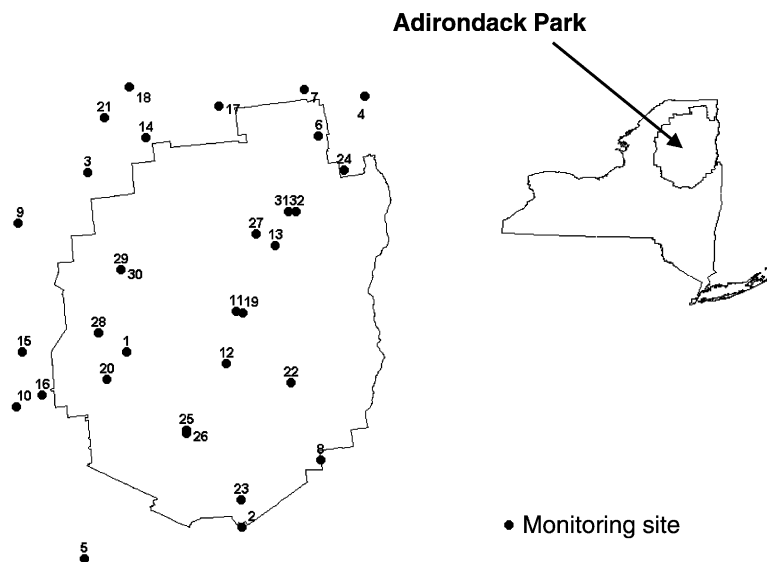


Fig. 1. Locations of monitoring sites for precipitation quantity, air temperature, and precipitation chemistry. The numbers correspond to the site numbers in Table 1.

used. Similarly, the values of NH_4^+ , Ca^{2+} , Mg^{2+} , K^+ , Na^+ , and Cl^- showed high variations and overall poor charge balances for the NYS-ADMN sites for the study period. Thus, only the NADP data was used for the latter solutes. Therefore, to calculate regional patterns of SO_4^{2-} and NO_3^- in wet deposition, we used the data from all six sites, while the data at the two NADP sites were used to determine wet deposition of NH_4^+ , H^+ , Ca^{2+} , Mg^{2+} , K^+ , Na^+ , and Cl^- .

2.2. Methods for the examination of spatial variability and the development of regression models

Analysis of variance was employed to test the differences among the sites in the SO_4^{2-} and NO_3^- concentrations in wet deposition. Mean separation was performed at the 5% level using protected least significant difference. Mean annual and monthly precipitation, mean monthly minimum and maximum temperatures and mean annual and quarterly concentrations of SO_4^{2-} and NO_3^- were estimated by applying multiple regression analyses using longitude, latitude, and elevation as independent variables. The coefficients of $p < 0.10$ were retained for the regression models to maintain more coefficients than would occur at the 5% level. Residuals were examined against independent variables. All potential outliers identified by visual examination were tested by externally studentized residuals at the 5% level. The extent of the influence of outliers on predicted values was evaluated by Cook's distance (Cook and Weisberg, 1982). Shapiro-Wilk W statistics were used to examine normality at the 5% level (Shapiro and Wilk, 1965). The nonparametric seasonal

Kendall test (Hirsch and Slack, 1984; Gilbert, 1987) was applied to examine monotonic trends in the monthly precipitation, minimum and maximum temperatures, and quarterly ion concentrations over the study period. Statistical analyses were conducted using SAS (SAS, 1994).

Six 1 degree digital elevation models with a grid width of 3 arc-second were obtained from the US Geological Survey to cover the Adirondack Park. A map of the boundary of the Adirondack Park in Arc/Info coverage was obtained from the Adirondack Park Agency. These spatial data were processed in Arc/Info version 8.0.2 and ArcView version 3.2 (Environmental Systems Research Institute, Inc.). The estimated precipitation, ion concentrations, and wet deposition of ions, and minimum and maximum temperatures were calculated externally. In estimating ion concentrations over the entire Adirondack region based on the data at a fewer sites, the minimum and maximum measured values among the monitoring sites were used as the maximum and minimum estimates for the entire grid cells so as to avoid unrealistic extrapolation outside of the measured data. Concentrations were expressed in mg compound l^{-1} and wet deposition was in kg compound $\text{ha}^{-1} \text{yr}^{-1}$.

3. Results and discussion

3.1. Temporal variability

3.1.1. Precipitation quantity and temperature

From 1988 to 1999, the monthly precipitation did not show significant temporal trends at most sites in and

near the Adirondack region ($p > 0.05$). While significant temporal changes in precipitation were detected for the upward trends at the Dannemora and Lawrenceville sites (Fig. 1, Table 1) and for the decreasing trend at the Highmarket site (Fig. 1, Table 1), the changes were small (median slope = 0.2, 0.1, and -0.2 cm yr^{-1} , respectively). Although the temporal changes were not significant at the 5% level at many sites, the sites in the northern Adirondacks and some of the sites in the southwestern region showed increasing trends in precipitation, while precipitation quantity declined at the sites in the central and southern region. Further, the precipitation consistently increased in summer and decreased in winter at all sites over the period from 1988 to 1999, though such changes were not significant at many sites ($p > 0.05$).

Continuous monitoring for these patterns for a longer period would be of management interest pertaining to possible climate change and its impact on the ecosystems in the Adirondack region. For our analysis, since the temporal changes in precipitation were not significant or minimal, the mean precipitation for the study period were considered to be adequate to predict spatial patterns in precipitation quantity.

Monthly minimum and maximum temperatures exhibited no significant changes at 60% of the sites (9 sites) from 1988 to 1999 ($p > 0.05$). Small but significant increases in minimum temperatures were found at the Chazy, Dannemora, Glens Falls Farm, Lake Placid, Massena, and Newcomb sites (Fig. 1, Table 1) with median slopes of 0.09, 0.07, 0.13, 0.11, 0.13, and

Table 1
The monitoring sites and their locations, data classes, and monitoring networks

Site number ^a	Site	Latitude (N)		Longitude (W)		Elevation m	Data	Monitoring network
		deg	min	deg	min			
1	Big Moose 3 SE	43	48	74	52	536	Precip	NCDC
2	Broadalbin	43	03	74	12	256	Precip	NCDC
3	Canton 4 SE	44	34	75	06	134	Precip, temp	NCDC
4	Chazy	44	53	73	26	52	Temp	NCDC
5	Chepachet	42	55	75	07	402	Precip	NCDC
6	Dannemora	44	43	73	43	408	Precip, temp	NCDC
7	Ellenburg Depot	44	55	73	48	262	Precip	NCDC
8	Glens Falls Farm	43	20	73	44	154	Precip, temp	NCDC
9	Gouverneur 3 NW	44	21	75	31	128	Precip, temp	NCDC
10	Highmarket	43	34	75	31	537	Precip	NCDC
11	Huntington Wildlife Forest	43	58	74	13	500	Conc	NADP/NTN
12	Indian Lake 2 SW	43	45	74	17	506	Precip	NCDC
13	Lake Placid 2 S	44	15	73	59	591	Precip, temp	NCDC
14	Lawrenceville 3 SW	44	43	74	45	152	Precip, temp	NCDC
15	Lowville	43	48	75	29	262	Precip, temp	NCDC
16	Lyons Falls	43	37	75	22	244	Precip	NCDC
17	Malone	44	51	74	19	268	Precip, temp	NCDC
18	Massena AP	44	56	74	51	65	Precip, temp	NCDC
19	Newcomb	43	58	74	11	494	Precip, temp	NCDC
20	Nicks Lake Campground	43	41	74	59	523	Conc	NYS-ADMN
21	Norfolk	44	48	75	00	70	Precip	NCDC
22	North Creek 5 SE	43	40	73	54	271	Precip	NCDC
23	Northville	43	10	74	12	241	Precip	NCDC
24	Peru 2 WSW	44	34	73	34	155	Precip, temp	NCDC
25	Piseco	43	28	74	31	527	Precip	NCDC
26	Piseco Lake	43	27	74	31	519	Conc	NYS-ADMN
27	Ray Brook	44	18	74	06	464	Temp	NCDC
28	Stillwater Reservoir	43	53	75	02	515	Precip, temp	NCDC
29	Wanakana Ranger School A ^b	44	09	74	54	460	Precip, temp	NCDC
30	Wanakana Ranger School B ^b	44	09	74	54	491	Conc	NYS-ADMN
31	Whiteface Mountain A ^b	44	24	73	52	610	Conc	NADP/NTN
32	Whiteface Mountain B ^b	44	23	73	52	625	Conc	NYS-ADMN

^aThe site numbers correspond to the values on Fig. 1. Abbreviations: precip: precipitation; temp: temperature; conc: concentration; NCDC: the National Climate Data Center; NADP/NTN: the National Atmospheric Deposition Program/National Trend Network; NYS-ADMN: The New York State Atmospheric Deposition Monitoring Network.

^bIndicate monitoring sites with the same names at different locations administered by different monitoring networks.

0.12°C yr⁻¹, respectively. Among the sites with increasing minimum temperatures, the Dannemora and Lawrenceville sites showed significant upward trends in maximum temperature as well (median slope = 0.03 and 0.11°C yr⁻¹, respectively). While four of six sites with increases in minimum temperatures were located around or outside the boundary of the Adirondack Park, the other two sites were at the center of the region with overall increases of >1°C in minimum temperatures during the past 10 yr. Long-term ecosystem studies would need to consider the effects of increases in temperature. In the present analysis, because the temporal changes in temperature were not significant or limited, the mean temperatures over the period examined were used to predict spatial patterns of temperature.

3.1.2. Ion concentrations

The quarterly concentrations of SO₄²⁻ significantly decreased during the period from 1988 to 1999 at all the six sites ($p < 0.05$). The SO₄²⁻ concentrations decreased at similar rates (median slopes = -0.061, -0.067, -0.061, -0.061, and -0.061 mg SO₄²⁻ l⁻¹ yr⁻¹ at HWF, WF-A, WF-B, Piseco-L, and Nicks, respectively), except at Wanakena Ranger School B (WRS-B) where the median slope of the decline was considerably smaller (-0.025 mg l⁻¹ yr⁻¹). The quarterly concentrations of SO₄²⁻ at the six sites were lower in winter and greater in summer, which are consistent with the observation by Driscoll et al. (1991) for this region. The annual mean concentrations of SO₄²⁻ differed at the six Adirondack sites ($p < 0.05$). Nicks showed the highest mean annual concentration of SO₄²⁻ (2.08 mg SO₄²⁻ l⁻¹) and Piseco-L, WRS-B, WF-B, HWF, and WF-A had mean annual concentrations of 2.00, 1.83, 1.63, and 1.60, and 1.49 mg l⁻¹, respectively. The mean annual concentrations at WF-A and WF-B were not different ($p > 0.05$).

In contrast to SO₄²⁻, the quarterly concentrations of NO₃⁻ exhibited no significant temporal trends from 1988 to 1999 ($p > 0.05$), except at HWF where a significant, but small rate of decline was detected during the study period (median slope = -0.025 mg NO₃⁻ l⁻¹ yr⁻¹). Nitrate exhibited greater concentrations in winter and lower concentrations in summer. Mean annual concentrations of NO₃⁻ were highest in Nicks (1.67 mg NO₃⁻ l⁻¹) among the six sites with values decreasing at Piseco-L, WRS-B, and HWF (1.56, 1.46, and 1.35 mg NO₃⁻ l⁻¹, respectively). WF-A and WF-B had the lowest concentrations (1.18 and 1.17 mg NO₃⁻ l⁻¹, respectively) and were not different from each other ($p > 0.05$). The spatial patterns of the mean annual concentrations of SO₄²⁻ and NO₃⁻ across the 6 sites were similar as found in the positive relationship between the mean annual concentrations of SO₄²⁻ and NO₃⁻ at these sites ($R^2 = 0.89$).

The annual mean concentrations of NH₄⁺, H⁺, Ca²⁺, Mg²⁺, K⁺, Na⁺, and Cl⁻ did not differ between the two NADP sites ($p > 0.05$). Both HWF and WF-A showed small, but significant declines in the concentrations of H⁺ and Cl⁻ (median slope = -1.12 and -0.60 μmol l⁻¹ yr⁻¹ for H⁺ and -0.0026 and -0.0016 mg l⁻¹ yr⁻¹ for Cl⁻, respectively). The Mg²⁺ concentrations decreased slightly only at HWF (-0.0004 mg l⁻¹ yr⁻¹). No significant temporal changes were found for the concentrations of NH₄⁺, Ca²⁺, K⁺, and Na⁺ at the two NADP sites from 1988 to 1999. Ammonium concentrations were greater in spring and summer than in winter at the NADP sites. The greater Cl⁻ concentrations in the first quarter of the year were consistent with the observations by Driscoll et al. (1991) for the region.

3.2. Relationships of precipitation quantity, minimum and maximum air temperatures, and ion concentrations with the spatial locations

3.2.1. Precipitation quantity

Multiple regression analyses suggested that the observed variations of 14–72% in mean annual and monthly precipitation were explained by longitude, latitude, and elevation. Greater than 50% of the variation in annual precipitation and monthly precipitation in 7 months were also explained by these independent variables (Table 2). Annual precipitation was related inversely to latitude and positively to longitude and elevation, suggesting an increasing pattern from the northeast to the southwest and with elevation (Table 2). While elevation is sometimes transformed when used as an independent variable (e.g., Brook et al., 1994), the use of the simple linear form is often appropriate as well (Daly et al., 1994). In our analysis, elevation was used as the simple linear form because the variations of residuals of regression models were not markedly improved although the log-form improved the normality of the elevation variable.

Mean monthly precipitation quantities were consistently related inversely to latitude and positively to longitude and elevation if the regression parameters were significant. This pattern suggested that precipitation increased from the northeast to the southwest and with elevation (Table 2). Precipitation in winter months and in May was related negatively to latitude and positively to longitude and elevation. Precipitation in spring months could be predicted only by latitude, whereas precipitation in summer months was dependent solely on elevation (Table 2). The precipitation in January was calculated by excluding one outlier ($p < 0.05$) (the Chepachet site) that is located outside the Adirondack Park (Fig. 1, Table 1). While the outliers were evident for precipitation in February and March

Table 2

Regression equations for mean monthly and annual precipitation quantity dependent on longitude, latitude, and elevation^a

Month or annual	Coefficients ^b				Mean (cm)	Adj. R^2	p
	Constant (cm)	Longitude (cm deg ⁻¹)	Latitude (cm deg ⁻¹)	Elevation (cm m ⁻¹)			
January	-10.64	1.806	-2.643	0.00492	9.04	0.73	<0.0001
February	-17.21	0.885	-0.997	0.00272*	5.78	0.50	0.0008
March	89.25		-1.866		7.07	0.59	<0.0001
April	51.34		-0.981		8.16	0.30	0.0033
May	47.97	0.558*	-1.858	0.00349	8.89	0.72	<0.0001
June	8.04			0.00324	9.17	0.21	0.0148
July	8.88			0.00393	10.13	0.30	0.0033
August	8.95			0.00323	9.98	0.14	0.0385
September	-89.65	1.308		0.00725	10.21	0.70	<0.0001
October	-65.32	0.985		0.00561	9.90	0.46	0.0006
November	-4.30	0.866*	-1.178	0.00477	9.93	0.51	0.0006
December	-26.13	1.297	-1.476	0.00482	7.09	0.56	0.0002
Annual	22.67	7.087	-10.444	0.04422	105.39	0.56	0.0002

^aNumber of monitoring sites was 24, except for January for which the Chepachet site (outside the Adirondack Park) was omitted.

^bCoefficients are significant at $p < 0.05$ with no mark or $p < 0.10$ with *.

(the Piseco site), based on the externally studentized residuals, these data were retained for the regression analyses because the Cook's D -values suggested that they did not sufficiently influence the predicted values at $\alpha = 0.05$ to call for remedial measures.

3.2.2. Minimum and maximum air temperatures

Longitude, latitude, and elevation accounted for 55–83% in the variation in minimum temperature and 54–74% in the variation in maximum temperature (Table 3). Minimum and maximum temperatures were negatively related to longitude, latitude, and elevation consistently if the regression coefficients were significant (Table 3). These results suggested a declining pattern in temperature from the southeast to the northwest and with elevation.

Minimum temperatures in winter months and maximum temperatures from January to April and in October and December were a function of longitude, latitude, and elevation (Table 3). Temperatures in other months were dependent on one or two of the independent variables. Elevation affected minimum and maximum temperatures during all months ($p < 0.05$). The changes in the relationship with longitude, latitude, and elevation among the months may have been associated with seasonal changes in the spatial gradient of temperature. One outlier was found for minimum temperatures in April (the Dannemora site) at the 5% level, but because the Cook's distance suggested that it did not sufficiently influence the predicted values at $\alpha = 0.05$ to call for remedial measures, it was included in the analysis.

3.2.3. Ion concentrations in precipitation and wet deposition

Multiple regression analyses of mean annual and quarterly SO_4^{2-} concentrations against longitude, latitude, and elevation found that the models accounted for 75–94% of the variation (Table 4). Mean annual SO_4^{2-} concentration was related positively to longitude and elevation and inversely to latitude. This relationship suggested an increasing pattern in the SO_4^{2-} concentrations from the northeast to the southwest and with elevation if the regression coefficients were significant. The relationship with longitude, latitude, and elevation differed for the quarters of the year. Annual and quarterly NO_3^- concentrations were functions of longitude and latitude (and elevation in quarter 3) (adjusted $R^2 = 0.96$ to 0.995, except for quarter 1, for which adjusted $R^2 = 0.76$) (Table 4). The positive relationships of NO_3^- concentrations with longitude and the inverse relationships with latitude suggested a similar geographic pattern in the NO_3^- concentrations to that observed for SO_4^{2-} .

3.3. Comparison of results with other regional regression models

3.3.1. Precipitation

Our regression model suggests that precipitation generally increased from the northeast to southwest and with elevation. Ollinger et al. (1995) predicted monthly precipitation based on the data of 310 weather stations across New York and New England from 1951 to 1980. Our results for the Adirondacks differed from the model of Ollinger et al. (1995), in which monthly

Table 3
Regression equations^a

Month	Coefficients ^b				Mean °C	Adj. R^2	p
	Constant (°C)	Longitude (°C deg ⁻¹)	Latitude (°C deg ⁻¹)	Elevation (°C m ⁻¹)			
<i>(a) Monthly mean minimum daily air temperature</i>							
January	159.43	-1.432	-1.466	-0.00397	-13.31	0.72	0.0007
February	137.48	-1.331	-1.129*	-0.00555	-13.28	0.62	0.0034
March	70.14	-1.029		-0.00639	-8.28	0.64	0.0008
April	33.56	-0.433*		-0.00621	-0.47	0.78	<0.0001
May	7.81			-0.00628	6.00	0.66	<0.0001
June	13.31			-0.00628	11.49	0.66	<0.0001
July	15.81			-0.00679	13.85	0.70	<0.0001
August	14.33			-0.00550	12.74	0.61	0.0003
September	9.54			-0.00492	8.12	0.55	0.0009
October	39.94	-0.486*		-0.00468	2.42	0.69	0.0004
November	50.86	-0.390*	-0.519*	-0.00576	-2.86	0.83	<0.0001
December	112.82	-1.039	-0.993	-0.00494	-9.99	0.82	<0.0001
<i>(b) Monthly mean maximum daily air temperature dependent on longitude, latitude, and elevation</i>							
January	114.29	-0.613	-1.582	-0.00259	-2.27	0.54	0.0086
February	140.44	-0.860	-1.732	-0.00296	-1.23	0.59	0.0046
March	141.31	-0.959	-1.471	-0.00394	3.55	0.55	0.0076
April	131.06	-0.805	-1.305	-0.00672	11.30	0.68	0.0013
May	68.31	-0.641		-0.00531	19.08	0.64	0.0009
June	70.56	-0.604*		-0.00559	23.98	0.65	0.0007
July	27.71			-0.00588	26.01	0.62	0.0003
August	26.51			-0.00548	24.93	0.61	0.0004
September	21.56			-0.00502	20.11	0.59	0.0005
October	97.94	-0.472*	-1.075	-0.00545	13.56	0.67	0.0016
November	39.54		-0.715*	-0.00567	6.21	0.74	<0.0001
December	86.37	-0.488*	-1.104	-0.00423	-0.15	0.59	0.0045

^a The number of monitoring sites was 15.

^b Coefficients are significant at $p < 0.05$ with no mark or $p < 0.10$ with *.

precipitation was related negatively to longitude and latitude and positively to elevation, suggesting an increasing pattern from the northwest to the southeast and with elevation. Ollinger et al. (1995) indicated that precipitation increased with decreasing distance to the ocean. For the smaller Adirondack region, the distance from the ocean did not appear to have a major effect on the geographic variations in precipitation. The climate associated with Great Lakes or the inland climate likely had a greater influence on precipitation.

In our analysis, the relationships between monthly precipitation and the spatial locations varied with season. In the winter months and in May, precipitation was related to all of the spatial location variables, while precipitation in most spring months was explained only by latitude, and those in the summer months were dependent solely on elevation (Table 2). Since the values of the regression coefficients for monthly precipitation did not vary with season, the presence of more regression variables in the equations for the winter

months suggests that monthly precipitation was spatially more variable in winter than in summer. Ollinger (1995) also reported that the spatial patterns in precipitation were more distinct in winter than in summer because the magnitude of regression coefficients was greater in the winter months in their regression equations. The differences in the regression coefficients and predictabilities for the Adirondack region between our empirical models and the models of Ollinger et al. (1993, 1995) were presumably due to the wider geographic coverage by the models of Ollinger et al. (Fig. 2).

3.3.2. Temperature

Our regression models for minimum and maximum temperatures suggest a decreasing pattern from the southeast to the northwest and with elevation. Ollinger et al. (1995) used minimum and maximum temperatures of 164 weather stations across New York and New England from 1951 to 1980 to predict monthly minimum

Table 4

(a-b). Regression equations for mean quarterly and annual (a) SO_4^{2-} and (b) NO_3^- concentrations dependent on longitude, latitude, and elevation.^a(c) mean of quarterly and annual concentrations of H^+ , NH_4^+ , Ca^{2+} , Mg^{2+} , K^+ , Na^+ , and Cl^- at the two NADP sites

Quarter or annual	Coefficients ^b				Minimum (mg l ⁻¹)	Maximum (mg l ⁻¹)	Mean (mg l ⁻¹)	Adj. R ²	p
	Constant (mg l ⁻¹)	Longitude (mg l ⁻¹ deg ⁻¹)	Latitude (mg l ⁻¹ deg ⁻¹)	Elevation (m)					
(a) SO_4^{2-} (mg SO_4^{2-} l ⁻¹)									
Quarter 1	-3.810	0.184	-0.213	0.00120*	0.47	2.13	1.13	0.94	0.037
Quarter 2	32.75		-0.697		1.17	3.88	2.08	0.75	0.016
Quarter 3	-60.25	0.844			1.08	4.16	2.56	0.76	0.014
Quarter 4	-6.03	0.289*	-0.351	0.00229*	0.44	2.18	1.26	0.89	0.065
Annual	-15.17	0.440	-0.388	0.00230*	0.88	2.48	1.77	0.94	0.034
(b) NO_3^- (mg NO_3^- l ⁻¹)									
Quarter 1	-28.80	0.409			0.95	2.59	1.59	0.76	0.0150
Quarter 2	11.71	0.144	-0.474		0.86	2.59	1.54	0.995	0.0002
Quarter 3	-15.97	0.401	-0.300	0.00116	0.76	2.41	1.30	0.99	0.0034
Quarter 4	-3.66	0.209	-0.239		0.51	2.41	1.35	0.96	0.0038
Annual	-5.10	0.248	-0.271		0.83	2.00	1.40	0.97	0.0019
(c) Other ions ($\mu\text{mol l}^{-1}$ for H^+ , mg compound l ⁻¹ for other ions)									
Quarter or annual	H^+ ($\mu\text{mol l}^{-1}$)	NH_4^+ (mg l ⁻¹)	Ca^{2+} (mg l ⁻¹)	Mg^{2+} (mg l ⁻¹)	K^+ (mg l ⁻¹)	Na^+ (mg l ⁻¹)	Cl^- (mg l ⁻¹)		
Quarter 1	33.49	0.133	0.065	0.010	0.008	0.051	0.100		
Quarter 2	37.25	0.247	0.102	0.017	0.016	0.036	0.076		
Quarter 3	42.14	0.230	0.070	0.011	0.010	0.027	0.063		
Quarter 4	28.82	0.154	0.060	0.011	0.019	0.042	0.081		
Annual	35.01	0.190	0.072	0.012	0.013	0.037	0.076		

^aIn calculating ion concentrations, for the concentrations less than minimum values should be changed to the minimum values listed and for those greater than maximum values should be changed to the maximum values listed in the table. The number of monitoring sites was 6.

^bCoefficients were significant at $p < 0.05$ without * or $p < 0.10$ with *.

and maximum temperatures. In their model, which differed from our regression model, minimum and maximum temperatures were negatively related to latitude and elevation, but positively related to longitude, suggesting a declining pattern from the southwest to the northeast, except for maximum temperature from January to March. The latitudinal gradient in temperatures in the models of Ollinger et al. (1995) was steeper in the winter months than in the summer months, owing to the greater magnitude of regression coefficients in the winter months. In our analysis, the steeper latitudinal gradients in both minimum and maximum temperatures in winter were due to the dependence on longitude or latitude in winter, but not in summer. The reverse in the geographic pattern in maximum temperature in winter in the regression equations of Ollinger et al. (1995) was not found in our analysis.

3.3.3. Concentrations of sulfate and nitrate

The regression model developed in our analysis suggests a pattern of increasing SO_4^{2-} concentrations from the northeast to the southwest in the Adirondacks.

The empirical relationship for annual SO_4^{2-} concentrations developed by Ollinger et al. (1993, 1995) was based on 3–11 yr of mean annual data from 26 NADP/NTN sites in the northeastern United States and was dependent solely on longitude, representing an increasing pattern from the east to the west. In our analysis, the positive relationships between the SO_4^{2-} concentrations and elevations were found annually and for quarters 1 and 4. However, inverse relationships of SO_4^{2-} concentrations with precipitation (Brook et al., 1994) and positive relationships with temperature (Brook et al., 1994; Buda and DeWalle, 2000) could suggest lower SO_4^{2-} concentration at higher elevation because precipitation increases and temperature decreases with increasing elevation. Yet, our empirical model predicted the concentrations closer to the measured values than the model of Ollinger et al. (1993, 1995) for the Adirondack region (Fig. 2).

The empirical relationship developed in our analysis suggests a pattern of increasing NO_3^- concentration from the northeast to the southwest in the Adirondacks. No significant influence of elevation was found for the

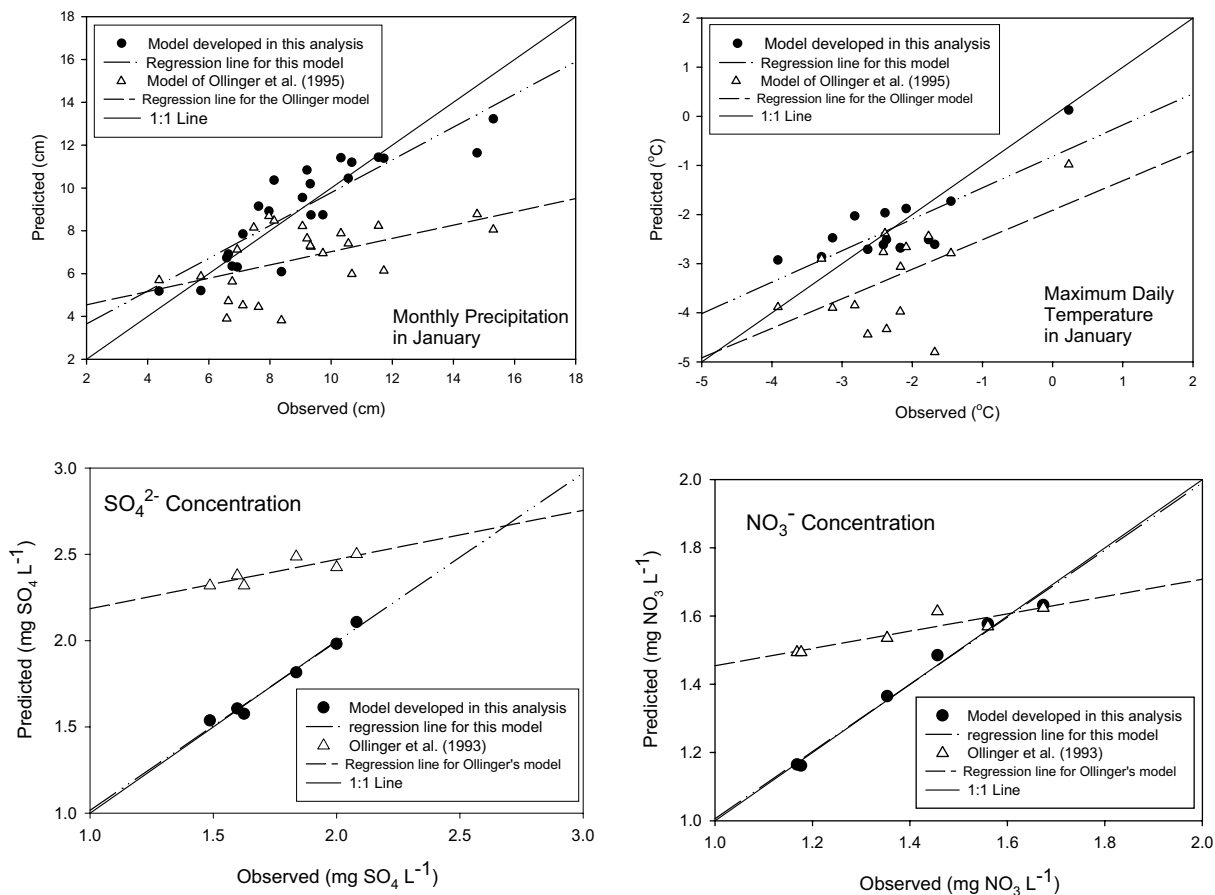


Fig. 2. Comparisons of predicted monthly precipitation quantity in January (a), monthly mean maximum daily air temperature in January (b), annual sulfate deposition in precipitation (c), and annual nitrate deposition in precipitation (d) by models developed in the present analysis and by Ollinger et al. (1995) with measured values.

NO₃⁻ concentration, except in quarter 3. The absence of significant elevational effect on NO₃⁻ was consistent with the lack of a relationship between the NO₃⁻ concentration and temperature found by Buda and DeWalle (2000), as temperature is normally inversely related to elevation. In the regression equation of Ollinger et al. (1993, 1995) for the northeastern US, the annual NO₃⁻ concentration was solely a function of longitude, suggesting an increasing pattern from the east to the west. The differences between our empirical models and the models of Ollinger et al. (1993, 1995) may be due to the differences in the spatial patterns of S and N precipitation chemistry on local versus wider regional scales. Our empirical models presumably captured local variability of precipitation chemistry which was probably caused in part by topographic features, such as mountains, highlands, and lakes, and local meteorology in the Adirondack region.

3.4. Prediction of precipitation, temperature, and wet deposition of major ions over the Adirondack region

Wet deposition of major ions over the Adirondack region was calculated as estimated precipitation multiplied by ion concentration based on the latitude, longitude, and elevation relationships. Predicted annual mean precipitation, monthly mean maximum temperature in January, wet deposition of SO₄²⁻ and NO₃⁻ over the Adirondack region were displayed as examples by projecting from the latitude–longitude coordinate system to the Universal Transverse Mercator system (Fig. 3). The estimated wet deposition of SO₄²⁻ and NO₃⁻ exhibited increasing patterns from the northeast to the southwest and with elevation.

As explained above, in estimating ion concentrations for the entire Adirondack region based on a few sites, the maximum and minimum measured values among the monitoring sites were used as the maximum and

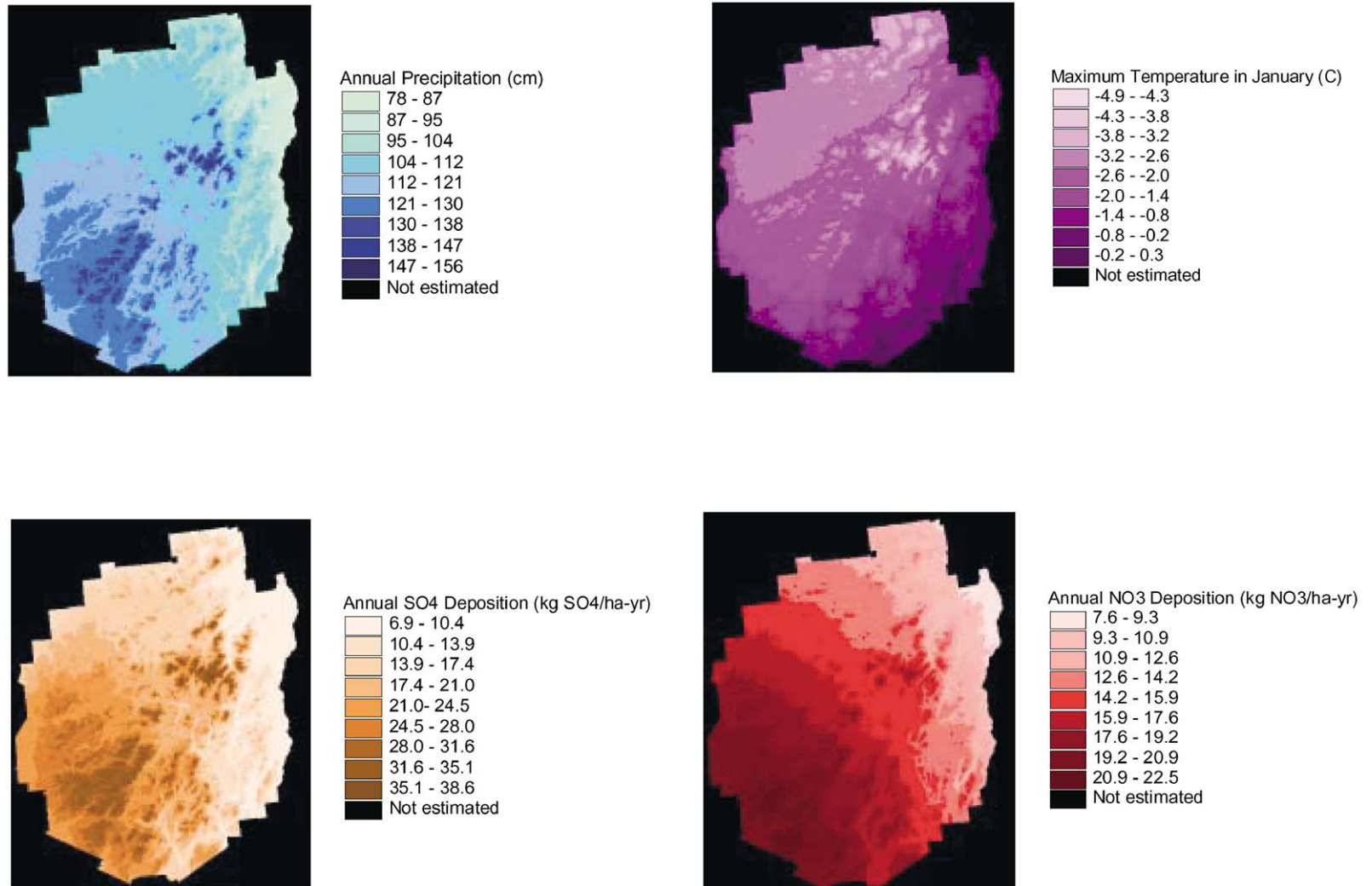


Fig. 3. Predicted annual precipitation quantity (a), monthly mean maximum daily air temperature in January (b), annual sulfate deposition in precipitation (c), and annual nitrate deposition in precipitation (d) over the Adirondack Park.

minimum estimates for the entire grid cells so as to avoid unrealistic extrapolation outside the measured data. As for precipitation and temperature, the monitoring sites covered nearly the entire Adirondack region with an elevation range of about 50 or 70 to 600 m. While measured data at high-elevation sites were sparse, the observation was reported for a 1050 m elevation site on Whiteface Mountain (44°22'N, 73°54'W) (Miller and Friedland, 1999). The annual precipitation amount predicted by our empirical model (129.5 cm) for this high elevation site was within a difference of 1% from the 10 yr (1986–1995) annual mean measured value (127.8 cm; from Miller and Friedland, 1999), compared with the predicted value by the model of Ollinger et al. (1993) for the sites above 400 m elevation (159.0 cm). These results suggest that our extrapolations for high-elevation sites are valid.

Since the quarterly SO_4^{2-} concentrations decreased at similar rates in five of six sites in the region from 1988 to 1999, the Clean Air Act Amendments of 1970 and 1990, which regulated atmospheric SO_2 emissions, appeared to be effective in curtailing SO_4^{2-} concentrations in precipitation uniformly throughout the region. Because precipitation quantity did not substantially change at most monitoring sites during the period examined, wet S deposition also declined in response to controls on SO_2 emissions.

Our study focused on the spatial patterns of precipitation and wet deposition along with that of temperature. Other forms of atmospheric deposition, including gas or vapor, aerosol, and cloud droplet, are also important contributors to total atmospheric deposition in the region. The spatial pattern of dry deposition differs from that of wet deposition and is generally more complex and difficult to be characterized (Clarke et al., 1997). Dry deposition at HWF located at the central Adirondacks ($2.5 \text{ kg N ha}^{-1} \text{ yr}^{-1}$) was nearly as much as the wet deposition of nitrate ($2.7 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ or $12.0 \text{ kg NO}_3 \text{ ha}^{-1} \text{ yr}^{-1}$; calculated from Mitchell et al., 2001) from 1991 to 1993, while at a site, Number Four, immediately outside the northwestern boundary of the Adirondack Park, dry deposition ($1.5 \text{ kg N ha}^{-1} \text{ yr}^{-1}$) was about 35% of wet nitrate deposition (calculated from Mitchell et al., 2001). Further, high-elevation forests receive greater atmospheric deposition in different forms, including precipitation, cloud droplet, and aerosol, due to orographic effects and the forest canopy structure (Miller and Friedland, 1999), although few studies have reported cloud and fog deposition (e.g., Anderson et al., 1999; Weathers et al., 1988) and long-term studies are scarce (e.g., Miller and Friedland, 1999). At 1050 m on Whiteface Mountain from the period from 1986 to 1999, the nitrate contribution of the sum of dry deposition and cloud water to the total atmospheric deposition exceeded the contribution of wet nitrate deposition by about 1.5 times, resulting in the

total NO_3^- deposition of $10.8 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ (or $47.7 \text{ kg NO}_3 \text{ ha}^{-1} \text{ yr}^{-1}$; calculated from Miller and Friedland, 1999). Similarly, 55% of the total sulfur deposition of $18.3 \text{ kg S ha}^{-1} \text{ yr}^{-1}$ (or $54.9 \text{ kg SO}_4 \text{ ha}^{-1} \text{ yr}^{-1}$, calculated from Miller and Friedland, 1999) was attributable to the combination of dry deposition and cloud water (Miller and Friedland, 1999). Therefore, the wet deposition values predicted by our models should be regarded as near the lower limits of total atmospheric deposition, especially at high-elevation areas.

Regional patterns in precipitation and wet deposition are decisive for the interpretation and prediction of ecosystem response to acidic deposition. The distribution of acidic ($\text{ANC} < 0 \mu\text{eq l}^{-1}$) and acid-sensitive ($\text{ANC} < 50 \mu\text{eq l}^{-1}$) lakes in the Adirondacks reflects these observed patterns of precipitation and deposition because the greatest density of acidic and acid-sensitive lakes are located in the Oswegatchie-Black River Basin in the southwestern Adirondacks (Kretser et al., 1989; Driscoll et al., 1991). Low ANC lakes in the southwestern Adirondacks also coincide with high-elevation watersheds with generally shallow deposits of glacial till (Driscoll et al., 1991). This combination of factors, including elevated precipitation, high wet deposition, and low rates of supply of basic cations due to shallow hydrologic flowpaths associated with their surficial geology, demonstrates why in the southwestern Adirondacks lake-watersheds are severely impacted by acidic deposition (Driscoll et al., 1991). Regional patterns in atmospheric deposition are also evident for the lakes in the Oswegatchie-Black River Basin that generally exhibit elevated concentrations of NO_3^- , compared to the lakes in other regions of the Adirondacks.

Our regional analysis of precipitation quantity and chemistry and air temperature can be used in the application of acidification models to the region. These models often utilize precipitation, air temperature, and atmospheric deposition as drivers for predicting soil and drainage water chemistry in watersheds (e.g., Gbondo-Tugbawa et al., 2001). Improved model inputs will allow for more accurate model predictions for the Adirondack region.

4. Conclusions

The variations in the mean annual and monthly precipitation amount, monthly mean minimum and maximum temperatures, and annual and quarterly concentrations of SO_4^{2-} and NO_3^- during the period from 1988 to 1999 were largely explained by the regression models using longitude, latitude, and elevation as independent variables for the Adirondack region. Spatial variability in the concentrations of other major ions was not found in this region. Wet deposition of SO_4^{2-} and NO_3^- varied spatially in concert with

precipitation quantity and the SO_4^{2-} and NO_3^- concentrations, and generally increased from the northeast to the southwest in the Adirondacks.

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