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CLIMATOLOGIC ANALYSIS FOR SNOW MITIGATION IN NEW YORK STATE

Final Report

Prepared for

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By

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INTRODUCTION

This report summarizes the data, analyses and conclusions regarding default values for weather variables that are needed to design snow mitigation measures as described in the 1994 publication *Design Guidelines for the Control of Blowing and Drifting Snow*, Strategic Highway Research Program (SHRP) Report SHRP-H-381 (Tabler 1994a). The analyses reported here followed the methods and procedures described in the SHRP report.

The algorithms developed herein provide estimates of the climatologic parameters needed to calculate seasonal snowfall and the mass transport and direction of blowing snow, in the absence of site-specific data provided by the user of the snow mitigation program. It is incumbent on the user, however, to verify that the default estimates are appropriate for a specific project. In particular, the critical wind direction for designing snow mitigation measures for a particular site often depends on site-specific factors such as local topography and vegetation that are not reflected in the default values.

DEFINITIONS AND NOTATION

Average monthly temperature (T_{ave}): calculated from the mean monthly maximum (T_{max}) and mean monthly minimum (T_{min}) temperatures as follows:

$$T_{ave} = (T_{max} + T_{min})/2 \tag{1}$$

Fetch: The distance contributing blowing snow to a downwind location (Figure 1). The upwind extent of the fetch is marked by some feature across which there is no appreciable snow transport, such as a wooded area, open water, a topographic feature causing snow deposition, or a plowed road with snow berms that cause blowing snow to be deposited.

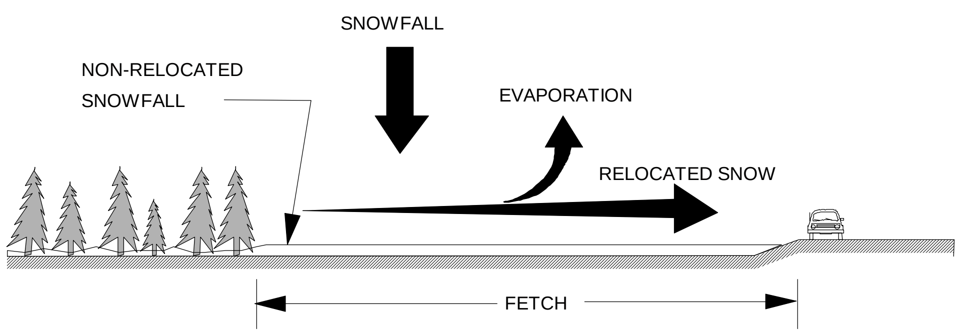

Figure 1. Illustration of fetch and other terms used in this report.

Potential snow transport (Q_{upot}): the total mass of blowing snow, per unit width across the wind in the first 5 m above the surface, if snow and fetch were unlimited, calculated from hourly wind data (the subscript *u* is a commonly used notation for wind speed).

Potential snow transport (Q_{spot}): the total mass of blowing snow per unit width across the wind, if all snowfall over the snow accumulation season were relocated by the wind (i.e., if wind were unlimited). The subscript *s* is a commonly used notation for snowfall.

Relocation coefficient (C_R): the ratio of relocated snowfall to total snowfall over the snow accumulation season.

Snow accumulation season: the period of drift growth that begins with the first blowing snow even that causes drifts persisting through the winter, and ends when snowdrifts reach maximum volume for the winter. The snow accumulation season is delimited by the dates when average air temperature reaches 0 °C, as computed from mean monthly temperatures.

Snowfall (S): the depth of snow that falls over a specified period of time, measured daily (or more frequently) so as to minimize the effects of melt, settlement and metamorphosis. In the databases used for this study, snowfall is reported in inches, and all regression equations retain the original units. Where S appears in engineering equations, units are usually in meters unless otherwise specified. Snowfall over the snow accumulation season is denoted as S_{AS}, and S_T represents total annual snowfall.

Snowfall water-equivalent ($S_{we,AS}$): the water-equivalent of the snowfall over the accumulation season, here assumed to be 10% of the snowfall:

$$S_{we,AS} = 0.1 S_{AS} \tag{2}$$

Where $S_{we,AS}$ is used in equations for calculating mass transport, units are in millimeters unless otherwise specified.

Snow transport (Q): the mass of snow transported by the wind over a specified time and width across the wind. In this report, snow transport refers to the total mass over the snow accumulation season, within the first 5 m above the surface, per meter of width across the wind.

Wind direction: the direction from which the wind is blowing, which in this report is expressed in degrees azimuth measured in a clockwise direction from true north—e.g., a wind direction of 270° means the wind is blowing directly from the west.

Wind speed (U): varies with height above the ground because of the retarding effect (drag) of the earth's surface, including low-growing vegetation, trees, or developed areas consisting of buildings and related features. Unless otherwise specified, *wind speed* as used in this report refers to the wind speed at 33 feet (10 meters) above the ground surface.

DATA SOURCES

The data sources for this study were those compiled by the National Climate Data Center (NCDC), as available on compact disk (CD-ROM) from EarthInfo, Inc. Air temperature and snowfall data were from the NCDC "Summary of the Day" (all years of record through 1997) and hourly wind data were from the NCDC "Surface Airways" data set, 1964-95, in which direction is reported to 36 compass points (e.g., 10°, 20°, etc.). Because wind direction data prior to 1964 were only reported to the nearest 16 compass points (e.g., N, NNW, NW, WNW, etc.) these data were not used for the analyses reported here. Supplementary information on wind directions associated with blowing snow was obtained by questionnaire sent to maintenance personnel of the New York State Department of Transportation. The responses obtained from these questionnaires consisted of arrows drawn on detailed road system maps.

Corresponding values for latitude, longitude and elevation were determined by locating the sites on DeLorme Topo USA™ V.2 maps on CD ROM. These data are included as an Appendix to this report.

RESULTS

Snow Accumulation Season

The snow accumulation season was calculated from mean monthly temperatures using the method described by Tabler (1988, 1994a), for all cooperative observer stations in, and adjacent to, New York State, having 10 or more years of temperature record. Qualifying stations in adjacent states were those situated within 30 minutes latitude or longitude of New York State boundaries. Mean monthly temperatures and calculated dates of the snow accumulation season are presented in Appendix A. Multiple regression analysis was used to develop a prediction equation for the fall and spring dates for the snow accumulation season using elevation, latitude, and longitude as the independent variables. Of the 269 qualifying stations (Table 1, Figure 2, Appendix A), ten were excluded from the regression analysis because the mean temperature for all months was above 0 °C, presumably due to "urban heating" near the more densely populated areas in the southern part of the state. The excluded stations were ID numbers 2964, 3786, 4130, 5796, 5803, 5804, 5811, 5816, 7633, and 7545.

Table 1. Qualifying stations used for snow accumulation season analysis.

State	Number of stations
CT	12
MA	6
NJ	18
NY	195
PA	29
VT	9
Total	269

Dates for the snow accumulation season are closely approximated by the following equations:

$$\textbf{Fall Date} = \mathbf{642.3 - 0.0361{*}Elev - 6.922{*}Lat} \qquad [R^2 = 0.770;\ \text{s.e.} = 5.69] \qquad (3a)$$
$$\textbf{Spring Date} = \mathbf{-284.8 + 0.0395{*}Elev + 8.101{*}Lat} \qquad [R^2 = 0.816;\ \text{s.e.} = 5.61] \qquad (3b)$$

where *Elev* is elevation in meters, *Lat* is latitude in degrees, R^2 is the square of the correlation coefficient, and s.e. is the standard error of the regression. Adding longitude as an independent variable did not reduce residual error significantly. As indicated by the standard errors, these relationships are good predictors, giving estimates that agree with about 95% of the actual values by within 3 days. For the 269 qualifying stations comprising the original database, the predicted fall date varies from November 11 to December 27, and the spring dates range from February 13 to April 7.

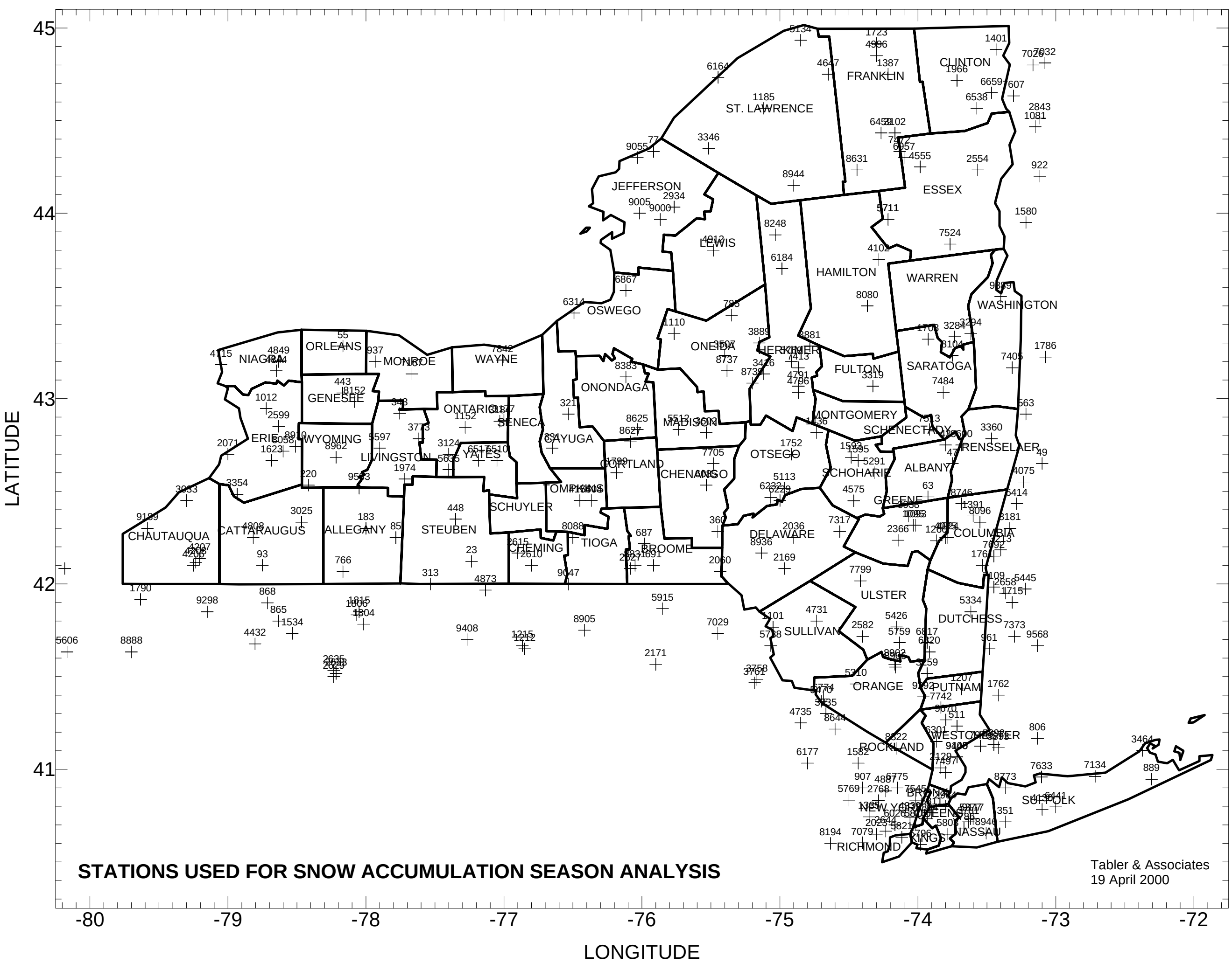

Figure 2. Location of stations used for snow accumulation season analysis.

Snowfall

Stations used for the snowfall analysis had to meet the same requirements as established for the snow accumulation season analysis—a minimum of 10 years of record, and location within or adjacent to (within 30 minutes latitude / longitude) New York State. The number of qualifying stations, by state, is shown in Table 2, and locations are plotted in Figure 3. The snowfall over the snow accumulation season is calculated as the sum of values for whole months within the accumulation season, plus the snowfall in partial months prorated on the basis of the number of days within the moth that fall within the snow accumulation season. For example, snowfall over an accumulation season extending from December 7 to March 3 would be calculated as ((25/31)*December snowfall + January snowfall + February snowfall + (3/31)*March snowfall). Mean monthly snowfall, annual totals, and totals over the snow accumulation season, are tabulated in Appendix B.

Table 2. Qualifying stations used for snowfall analysis.

State	Number of stations
CT	23
MA	15
NJ	45
NY	330
PA	60
VT	24
Total	497

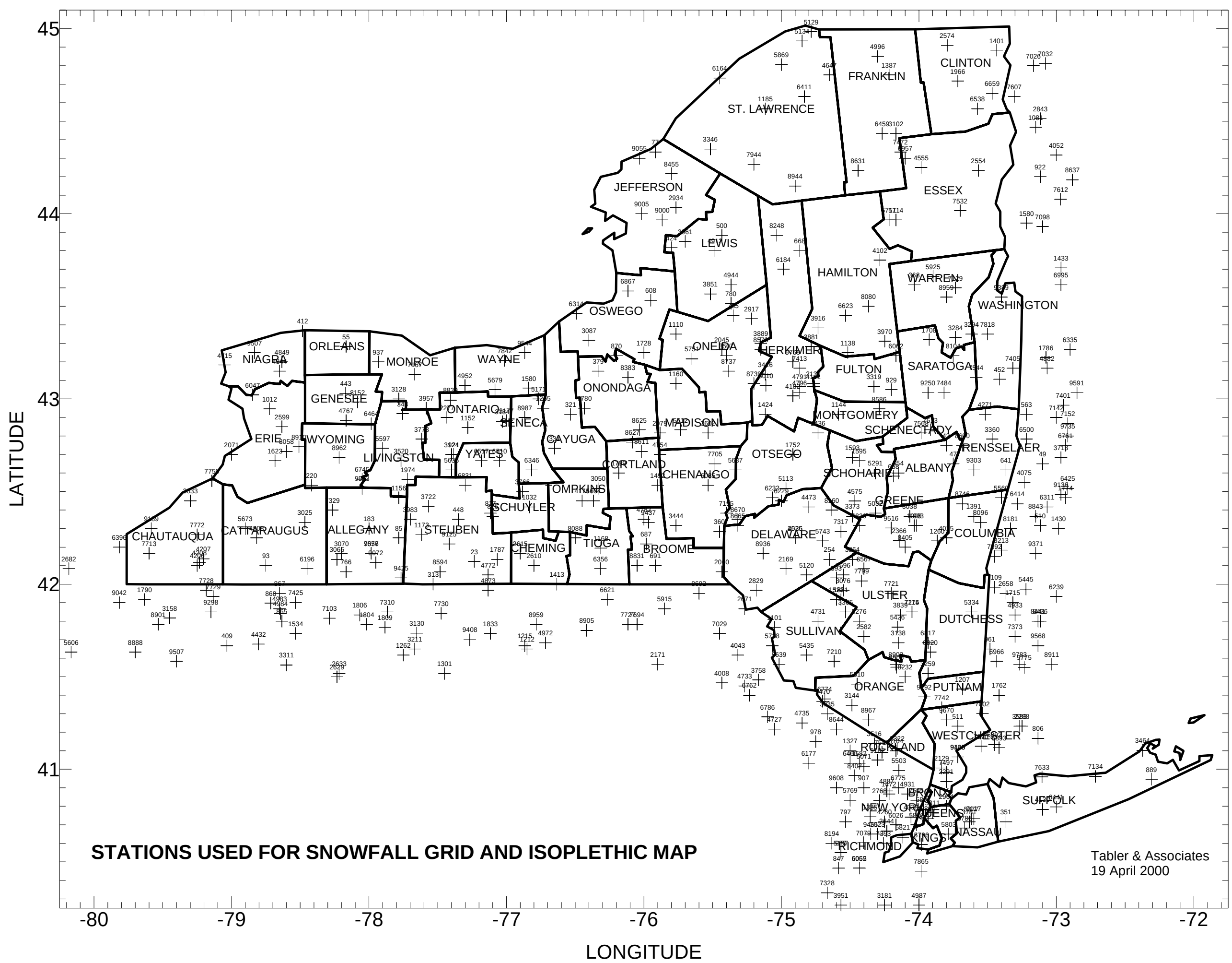

Figure 3. Location of stations used for snowfall analysis.

Regression analysis was used to determine if elevation, latitude and longitude could be used to estimate snowfall with sufficient accuracy. This analysis indicated snowfall was not related to longitude, but was strongly correlated with elevation and latitude:

$$\mathbf{S_T = -686.6 + 0.083{*}Elev + 17.251{*}Lat} \qquad [n = 497;\ R^2 = 0.553;\ s.e. = 22.45] \qquad (4)$$

$$\mathbf{S_{AS} = -695.4 + 0.076{*}Elev + 17.108{*}Lat} \qquad [n = 497;\ R^2 = 0.626;\ s.e. = 18.61] \qquad (5)$$

where S_T is mean annual snowfall in inches, S_{AS} is mean snowfall over the snow accumulation season (inches), *Elev* is elevation in meters, and *Lat* is degrees north latitude.

The ratio of snowfall over the accumulation season (S_{AS}) to total annual snowfall (S_T) is closely approximated by

$$\mathbf{S_{AS} / S_T = -3.19 + 0.00028{*}Elev + 0.0841{*}Lat + 0.0034{*}Lon} \qquad [n = 497;\ R^2 = 0.888;\ s.e. = 0.039] \ (6)$$

where *Elev* and *Lat* are as previously defined, and *Lon* is degrees west longitude (positive). Equation (6) could be used to generate a grid for snowfall over the accumulation season by using it to adjust previously published isoplethic maps for total annual snowfall, as was speculated in the proposal for this study. Alternatively, new snowfall grids can be generated directly from the snowfall data, as described below.

Because of the relatively large standard errors associated with the regression equations for snowfall and the large number of stations comprising the dataset, more accurate estimates of snowfall at a point can be obtained using mathematical gridding methods to interpolate data from adjacent stations. Using the Surfer® 7 software program developed by Golden Software, Inc. (1999), the *point Kriging*[1] method, with the default linear variogram, was used to develop a grid consisting of 423 columns between –71.75 and –80.1833° longitude, and 237 rows between 40.2667 and 44.983° latitude. This corresponds to approximately 0.97 miles between grid nodes longitudinally, and 1.23 miles latitudinally. The grid files blanked for New York State boundaries are presented as ASCII XYZ files, designated as "TASF grid.dat" and "SASSF grid.dat" on the enclosed disk. It is recommended that these grids, or maps derived therefrom, be used for snowfall estimates in algorithms requiring values for these variables. It is to be noted that the grid file for snowfall over the accumulation season submitted here supersedes a preliminary version submitted 18 January 2000, which contained errors for the snowfall values for stations in New Jersey.

The isopleths of total annual snowfall derived here (Figure 4) are similar to those presented in the publication *Climate of New York* (United States Department of Commerce 1972) (Figure 5). The enhanced detail resulting from geostatistical gridding exposes some apparent aberrations or inconsistencies, such as the low in Orange County. If these anomalies are later shown to be artifacts of measurement errors, they can be easily corrected by changing the *Z* values for specific nodes using the editing tools available in the Surfer® software.

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[1] Kriging is a geostatistical gridding method that produces maps from irregularly spaced data. Kriging expresses trends in data; e.g. high points are represented as a ridge rather than as isolated bull's-eye contours. Detailed descriptions are to be found in Cressie (1990) and Abramowitz and Stegun (1972).

An isoplethic map of snowfall over the snow accumulation season, developed from the grid file for this parameter, is plotted in Figure 6.

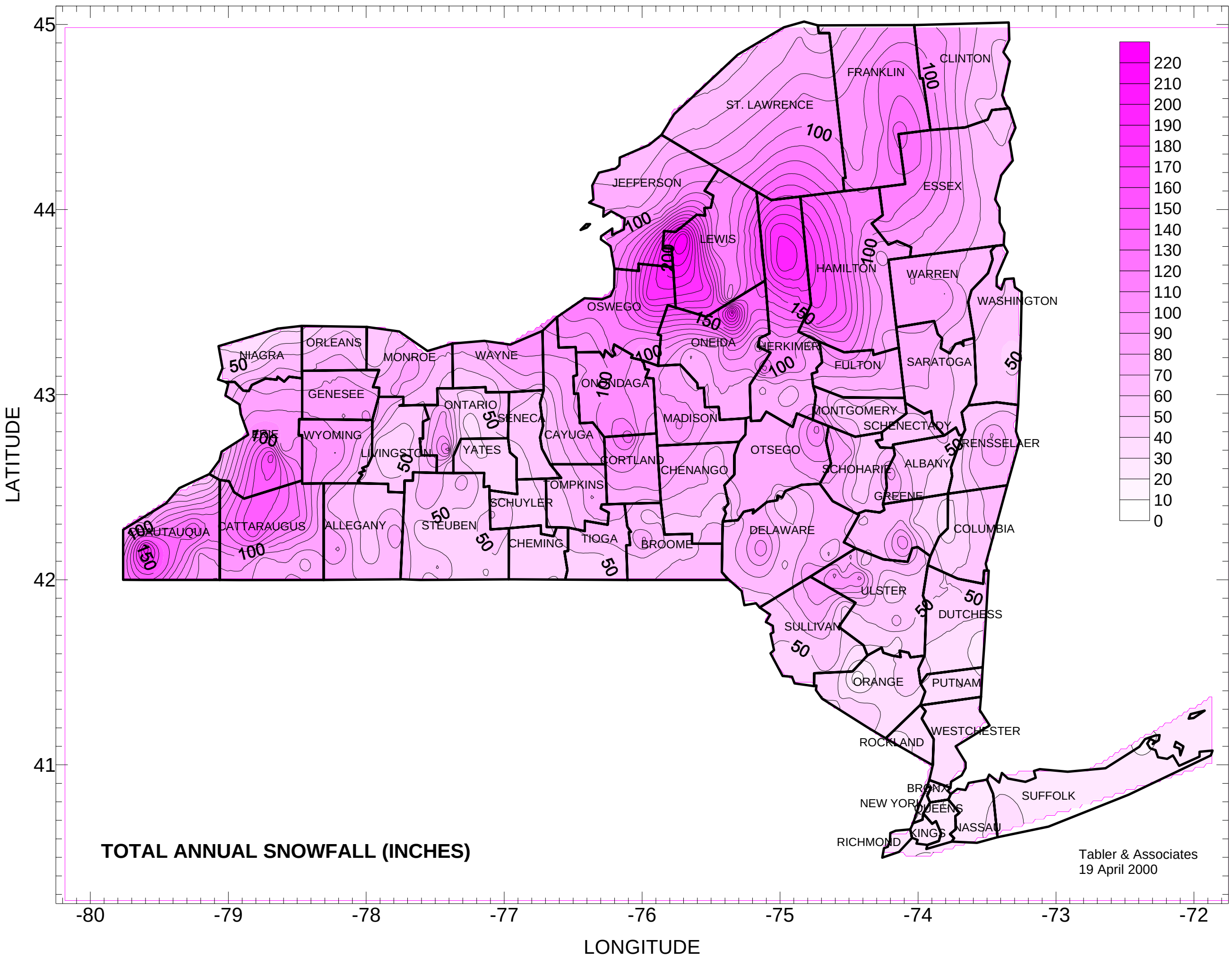

Figure 4. Isoplethic map of total annual snowfall derived from the "*TASF* grid.dat" file.

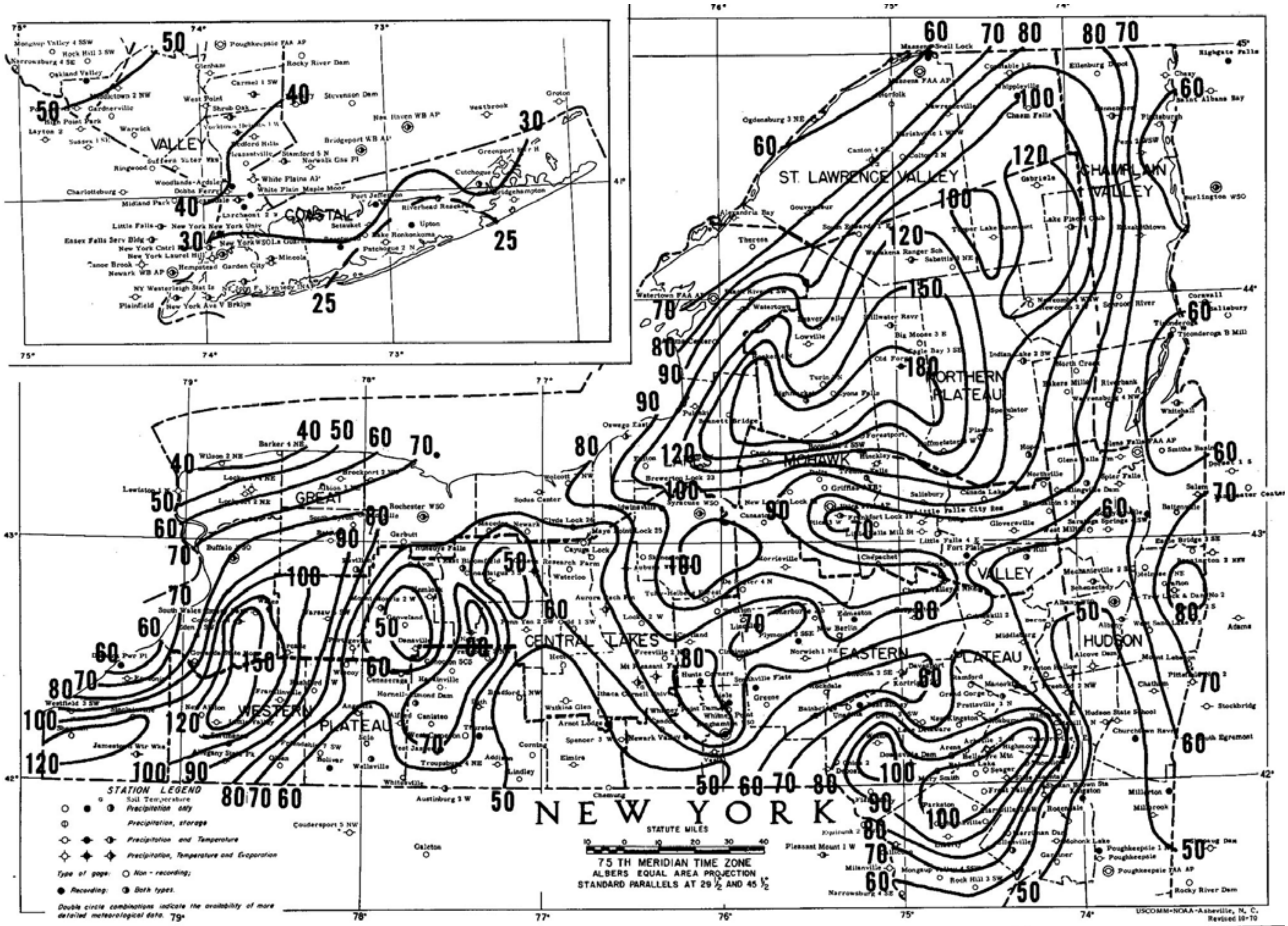

Figure 5. Isoplethic map of total annual snowfall appearing in "*Climate of New York*," NOAA Publication No. 60-30 (1972).

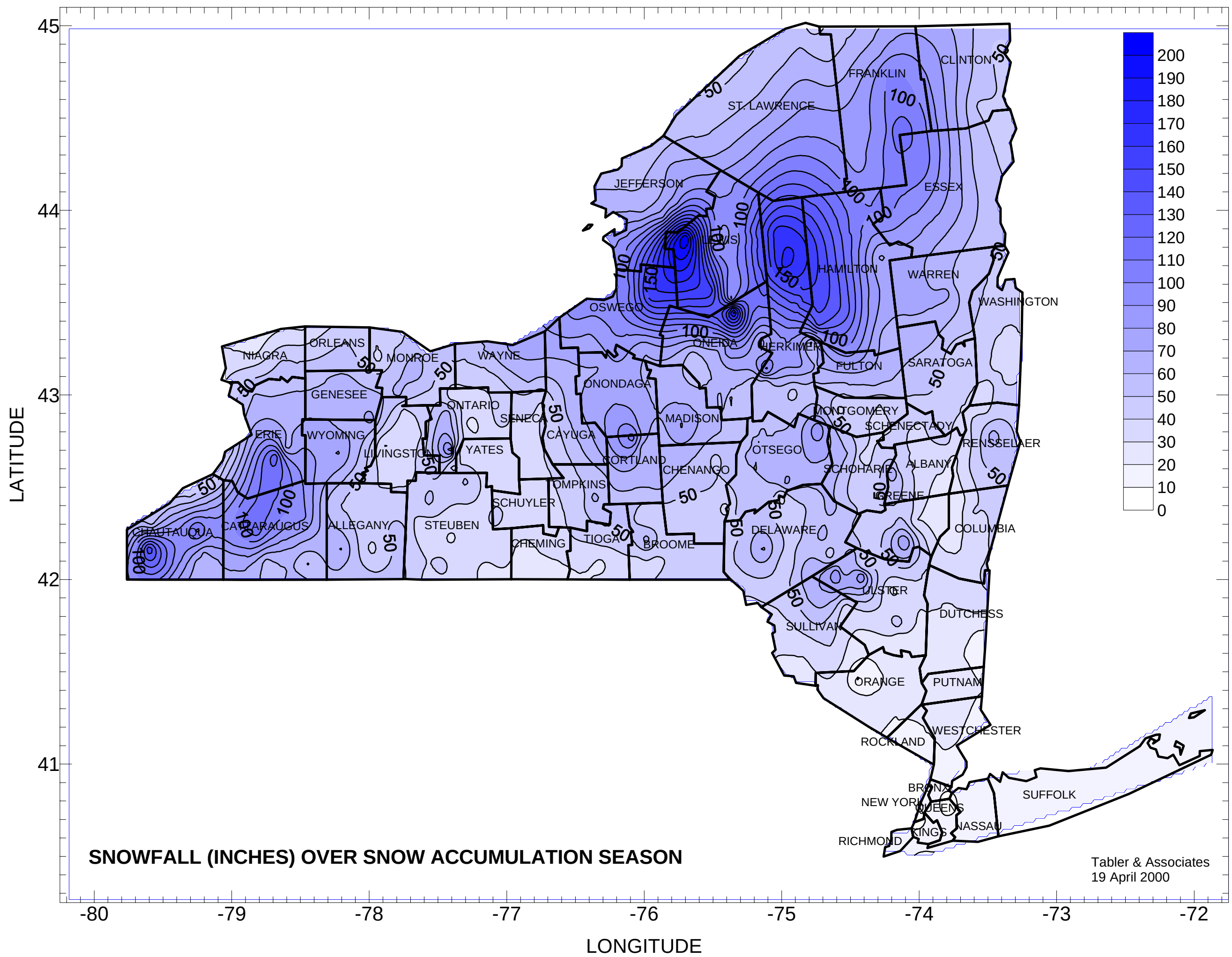

Figure 6. Isopleths of snowfall over the snow accumulation season, derived from the "*SASSF grid.dat*" grid file.

Potential Snow Transport from Wind Data

If snow and fetch are unlimited, snow transport in the first 5 m above the ground surface varies with wind speed according to

$$Q_{0\text{-}5} = U_{10}^{3.8} / 233847 \tag{7}$$

where $Q_{0\text{-}5}$ is snow transport in kg/s per meter of width across the wind, and U_{10} is wind speed at 10 m height, in m/s (Tabler 1991). This relationship can be used to determine potential snow transport contributed by each wind speed/direction cell in a "wind rose" table. For each wind direction, the potential transport for the *ith* wind speed class is

$$Q_{upot} = (u_i^{3.8}/233847)(f)(86400)(n) \tag{8}$$

where Q_{upot} is the potential transport (kg/m), u_i is the midpoint of the *ith* 10-m wind speed class, and f is the frequency of observations within the u_i wind speed class over a month, or portion of a month, having n days (e.g., if the snow accumulation extended from December 21 to March 5, n for December and March would be 11 and 5, respectively). Because wind-measuring instruments at different stations are not always situated at the same height above the surface, and because wind speed increases with height within the atmospheric boundary layer, it is necessary to adjust wind data for the height of instrumentation. For this analysis, instrument height at the various locations was obtained from the publication by Changery (1978), and wind data for each station were adjusted to the standard 10-meter height using the commonly accepted $1/7^{th}$ power law to approximate the vertical distribution of wind speed (Sutton 1953, p. 238) for wind speeds above the threshold for blowing snow:

$$U_{10} / U_Z = (10/Z)^{1/7} \tag{9}$$

where U_{10} = wind speed at 10 meters, and U_Z = wind speed at height Z. The threshold for blowing snow was assumed to be 13 kts (15 miles/hour).

Potential snow transport was calculated from the hourly observations reported in the NCDC "Surface Airways" data set, 1964-95, for 15 of the 16 stations within, or adjacent to (i.e., within 30 minutes latitude/longitude), New York State (Table 3). The New York Central Park station (WBAN# 94728) was excluded at the suggestion of Dr. Jon Peterka[2], whose experience indicates that the wind data at this station are not representative of any area other than the immediate vicinity of the observation site. Although wind data are available from other sites, the analysis reported here was limited to stations for which data were available on EarthInfo, Inc., CD ROM, as specified in the proposal for this study.

Potential snow transport was calculated for each station for all dates in the snow accumulation season, as calculated from Equations (3a) and (3b), and a separate analysis was done restricting data to days when blowing snow was reported for "current weather," including dates outside of the snow accumulation season. The notation used for the results of these two methods is $Q_{upot,AS}$ and $Q_{upot,BS}$, respectively. For the blowing snow analysis, all hours of data were used for any day when "blowing snow" was noted for any hour—a convention adopted to simplify the otherwise onerous task of filtering hourly data. Although this convention tends to overestimate $Q_{upot,BS}$, it compensates for the likelihood that low-level transport with winds only slightly above the threshold for relocation would not always be detected by visual observation, especially at night or in the presence of snowfall. The results of the analyses for $Q_{upot,AS}$ and $Q_{upot,BS}$ are summarized in Table 4.

$Q_{upot,AS}$ represents an upper limit for snow transport that will always overestimate actual snow transport because there is not always movable snow on the ground when the wind speed exceeds the threshold for blowing snow. $Q_{upot,BS}$ would provide the best estimate of potential snow transport if the observations were accurate, all-inclusive, and not affected by local sheltering or obstructions. In the author's opinion, $Q_{upot,BS}$ provides the best estimate of potential transport for engineering applications, for stations where the observation location is adequately exposed. $Q_{upot,AS,}$ on the other hand, provides the best estimate of the prevailing wind direction associated with blowing snow because it represents a much larger sample size compared to limiting the analysis to days with blowing snow.

[2] Vice President, Cermak, Peterka and Petersen, Inc., Wind Engineering Consultants, Fort Collins, Colorado.

Table 3.—Descriptions, statistics, and estimated snow accumulation season for stations used for potential snow transport analysis.

Station Name	State	WBAN #	Latitude	Longitude	Elevation	Record begins	Record ends	Record years	Anem. height	Snow accumulation season: Fall	Spring	Length
			-deg N-	-deg. W-	-m-	-date-	-date-	-no.-	-m-	-date-	-date-	-days-
Binghampton Link Field	NY	4725	42.217	75.983	487.7	01/01/1964	10/31/1995	32	6.7	11/27	03/16	110
Islip, LI, MacArthur Field	NY	4781	40.783	73.100	25.6	01/01/1974	10/31/1995	18	6.1	12/24	02/15	54
New York LaGuardia	NY	14732	40.767	73.900	3.4	01/01/1964	12/31/1995	32	6.1	12/24	02/14	52
Buffalo Airport	NY	14733	42.933	78.733	214.9	01/01/1964	11/30/1995	32	6.1	12/02	03/11	100
Albany County Airport	NY	14735	42.750	73.800	83.8	01/01/1964	07/31/1995	32	6.1	12/08	03/04	88
Rochester Intl. Airport	NY	14768	43.133	77.667	182.9	01/01/1964	12/31/1995	32	6.1	12/02	03/11	101
Syracuse Hancock Airport	NY	14771	43.117	76.117	125.0	01/01/1964	07/31/1994	31	6.4	12/04	03/09	96
Massena Airport	NY	94725	44.933	74.850	65.2	01/01/1964	12/31/1995	32	6.1	11/23	03/21	119
New York Central Park	NY	94728	<------------------------------Not Used------------------------------>										
New York J. F. Kennedy AP	NY	94789	40.650	73.783	4.9	01/01/1964	12/31/1995	32	6.1	12/25	02/13	50
Watertown Airport	NY	94790	44.000	76.017	96.9	01/01/1964	12/31/1984	6	6.1	11/29	03/15	107
Bridgeport Sikorsky	CT	94702	41.167	73.133	3.0	01/01/1964	12/31/1995	32	10.0	12/22	02/17	58
Burlington	VT	14742	44.467	73.150	101.2	01/01/1964	12/31/1995	32	6.1	11/25	03/19	115
Newark	NJ	14734	40.700	74.167	3.0	01/01/1964	12/31/1995	32	6.1	12/25	02/14	51
Bradford Regional Airport	PA	4751	41.800	78.633	645.3	01/01/1964	10/31/1994	31	6.4	11/24	03/19	116
Erie International Airport	PA	14860	42.083	80.183	222.5	01/01/1964	09/30/1995	32	6.1	12/07	03/04	88

Table 4. Potential snow transport results (see Table 3 for station statistics).

			<--------Potential transport over snow accumulation season-------->								<------------Potential transport for days with blowing snow---------->										
Station Name	State	No. of snow accum. seasons	$Q_{upot,AS}$	Prevailing $Q_{upot,AS}$ direction	% $Q_{upot,AS}$ from prevailing direction	$Q_{upot,AS}$ from prevailing direction	Secondary $Q_{upot,AS}$ direction	% $Q_{upot,AS}$ from secondary direction	Days with blowing snow over record	Days with blowing snow per year	$Q_{upot,BS}$	$Q_{upot,BS}$ / $Q_{upot,AS}$	Prevailing $Q_{upot,BS}$ direction	% $Q_{upot,BS}$ from prevailing direction	Secondary $Q_{upot,BS}$ direction	% $Q_{upot,BS}$ from secondary direction	S_{AS}	S_{AS}	Q_{spot}	$Q_{upot,AS}$ / Q_{spot}	**$Q_{upot,BS}$ / Q_{spot}**
			-t/m-	-deg. az.-	-%-	-t/m-	-deg. az.-	-%-			-t/m-		-deg. az.-	-%-	-deg. az.-	-%-	-in-	-m-	-t/m-		
Binghampton Link Field	NY	31.69	42.18	290	76.0	32.06	153	20.9	324	10.2	12.45	0.30	296	88.7	135	3.4	64.71	1.64	246.55	0.17	**0.051**
Islip, LI, MacArthur Field	NY	17.00	20.67	291	77.9	16.10	38	13.6	54	2.5	4.78	0.23	303	63.8	44	31.7	11.17	0.28	42.56	0.49	**0.112**
New York LaGuardia	NY	32.02	49.38	303	80.2	39.60	43	13.3	43	1.3	6.05	0.12	47	54.1	322	44.2	12.19	0.31	46.44	1.06	**0.130**
Buffalo Airport	NY	31.71	100.47	248	96.3	96.75	61	3.7	469	14.8	39.73	0.40	253	96.5	51	2.9	62.09	1.58	236.56	0.42	**0.168**
Albany County Airport	NY	31.73	34.53	291	76.2	26.31	167	14.6	85	2.7	9.80	0.28	301	62.1	50	31.2	42.78	1.09	162.99	0.21	**0.060**
Rochester Intl. Airport	NY	32.00	57.70	257	90.4	50.56	20	1.1	508	15.4	26.84	0.47	264	88.1	24	5.6	65.69	1.67	250.28	0.23	**0.107**
Syracuse Hancock Airport	NY	30.72	47.34	268	85	40.24	80	3.7	429	14.0	25.00	0.53	269	97.4	86	2.2	73.11	1.86	278.55	0.17	**0.090**
Massena Airport	NY	32.01	24.63	257	69.8	17.19	67	25.1	290	9.1	6.31	0.26	261	56.3	66	39.7	59.24	1.50	225.70	0.11	**0.028**
New York J. F. Kennedy AP	NY	31.88	48.25	308	88.4	42.66	34	8.2	73	2.3	7.39	0.15	320	70.8	38	28.6	11.69	0.30	44.54	1.08	**0.166**
Watertown Airport	NY	6.01	39.32	229	87.1	34.25	40	5.4	65	10.8	12.97	0.33	237	86.1	39	6.5	67.6	1.72	257.56	0.15	**0.050**
Bridgeport Sikorsky	CT	31.85	45.21	296	74.9	33.86	52	20.7	55	1.7	6.10	0.14	51	51.5	316	40.5	14.45	0.37	55.05	0.82	**0.111**
Burlington	VT	32.02	36.24	308	39.2	14.21	170	57.9	155	4.8	4.11	0.11	312	71.1	168	25.7	61.65	1.57	234.89	0.15	**0.017**
Newark	NJ	32.00	25.46	294	83.8	21.34	23	8.2	39	1.2	3.25	0.13	295	66.4	30	32.6	56.45	1.43	215.07	0.12	**0.015**
Bradford Regional Airport	PA	30.68	17.89	275	78.5	14.05	143	14.3	832	27.1	10.74	0.60	281	87.7	147	5.2	68.78	1.75	262.05	0.07	**0.041**
Erie International Airport	PA	31.73	59.11	221	90.3	53.37	51	4.6	492	15.5	27.68	0.47	251	86.5	50	7	48.12	1.22	183.34	0.32	**0.151**
AVERAGES			43.22	275.7					260.9	8.90	13.55	0.30							182.81	0.37	**0.087**

NOTATION:

S_{AS} = snowfall over snow accumulation season

$Q_{upot,AS}$ = Potential snow transport determined from all wind data over snow accumulation season, for all data since 01 January 1964

$Q_{upot,BS}$ = Potential snow transport determined from wind data for all days reporting blowing snow, for all data since 01 January 1964

Q_{spot} = Potential snow transport (t/m) for an infinite fetch, calculated from: Q_{spot}= 0.001(0.5 * 3000 * $S_{WE,AS}$), where $S_{WE,AS}$ is in millimeters

Potential Snow Transport from Snowfall Data

The maximum potential snow transport is that which would result downwind of an infinite fetch if the entire snowfall over the accumulation season were relocated by the wind. This potential transport, denoted Q_{spot} (in kg/m), is calculated from the total snowfall over the snow accumulation season ($S_{we,AS}$, in millimeters) using the expression (Tabler 1994a)

$$Q_{spot} = 1500S_{we,AS} \tag{10}$$

Equation (10) was derived from a conceptual model for evaporation with empirically derived coefficients (Tabler 1975), and constitutes the generally accepted method for estimating potential transport from snowfall data. Values for Q_{spot} for the wind data stations are included in Table 4.

Estimating Snow Transport for Designing Mitigation Measures

The snow transport at a specific site, Q (kg/m), as required to design mitigation measures, is given by

$$Q = C_R*Q_{spot}*(1 - 0.14^{F/3000}) = 1500*C_R*S_{we}*(1 - 0.14^{F/3000}) \tag{11}$$

where C_R is the relocation coefficient and F is fetch distance, in meters (Tabler 1975, 1994a). The ratio $Q_{upot,BS} / Q_{spot}$, also shown in Table 4, provides an estimate of C_R. It is hypothesized that the highest values for C_R, 0.17 at New York JFK and Buffalo, represent the best estimate for a statewide relocation coefficient, and that lower values at other locations are caused by a combination of local sheltering, instrument siting, and differences in observational techniques. This value for C_R compares favorably with the average of 0.22 measured over the period 12/24/93 to 3/4/94 during a study on US Route 219 south of Buffalo (Tabler 1994b).

It is therefore proposed that for designing snow mitigation measures, snow transport, *Q (kg/m)* should be estimated from

$$\mathbf{Q = 1500(0.17)(S_{we,AS})(1 - 0.14^{F/3000})} \tag{12}$$

where snowfall water-equivalent ($S_{we,AS}$) is in millimeters, and fetch (F) is in meters. To illustrate the estimates this equation would generate, fence heights required at locations where fetch was infinite would range from 1.0 m at New York LaGuardia & JFK, to 2.0 m at Buffalo and 2.2 m at Syracuse. Where snowfall was 150 inches, the required fence height would be 3.0 m. These fence heights were calculated from the relationship between snow storage capacity, Q_c (in t/m) and fence height, H (in meters)(Tabler 1994a)

$$Q_c = 8.5\ H^{2.2} \tag{13}$$

First order approximations for fetch distances at a specific location can be readily determined from topographic quadrangle maps available on compact disk from DeLorme ("3-D TopoQuads™"). Complete coverage of New York State is available as a 5-disk set for approximately $100.

Prevailing Direction of Blowing Snow

Wind directions associated with blowing snow problems are so dependent on local terrain, road geometry, and vegetation that the designer should be required to specify a direction applicable for a project location based on site-specific observations. The responses to the questionnaire sent out to NYSDOT maintenance personnel, however, support the intuitive supposition that certain directions are more frequently associated with blowing snow problems than others, and that the prevailing directions associated with blowing snow are somewhat predictable within a given region.

Where wind data are available, the prevailing directions of snow transport can be calculated from wind rose data by using Equation (7) as a weighting parameter, and this calculation was performed as part of the potential transport (Q_{upot}) analyses using an automated subroutine. An example of the procedure for Albany is shown in Table 5. The total transport from each direction (Column (1)) is listed in Column (2). The direction column is extended beyond 360° to allow prevailing directions to be calculated for modes extending through Due North, although this provision was unnecessary at Albany. Column (3) is the product of (Direction * Transport). Transport from a given direction is arbitrarily deemed significant if it exceeds 1% of the total (10,955 kg/m at Albany). If this criterion is met, then (Direction*Transport) is accumulated in Column (4), Transport is accumulated in Column (5), the average direction (Column (6)) is calculated as (Column (4))/(Column (5)), and the percent of total transport (100*Column(5)/total transport) is shown in Column 7. These calculations indicate that at Albany, 76% of the snow transport is from an average direction of 291°, and 15% is from 167°.

Primary and secondary directions determined in this manner are included in Table 4 for the 15 stations analyzed in this study, for both total wind data over the snow accumulation season, and for only days when blowing snow was reported. Primary directions over the snow accumulation season are plotted in Figure 7, in addition to the directions reported by NYSDOT personnel for 290 specific problem locations.

Regression analysis relating wind directions (in degrees, True North azimuth) to latitude and longitude yield the following relationships:

$Q_{upot,AS}$: **Direction = 987 – 9.42*Lon** [n = 15; R^2 = 0.579; s.e. = 18.14] (14)

$Q_{upot,BS}$: Direction = 1899 – 16.47*Lat – 11.97*Lon [n = 15; R^2 = 0.521; s.e. = 35.57] (15)

Questionnaire: Direction = 751 – 11.09*Lat [n = 290; R^2 = 0.018; s.e. = 45.42] (16)

Equation (14) provides the best prediction algorithm, and is recommended for calculating default directions in the absence of site-specific data. Although Equation (16) is statistically significant at the 95% confidence level, it has no value for predictions. Factors limiting the utility of the questionnaire include

- No responses were received from several regions comprising about half of the state
- Respondents seldom used a resolution finer than 8 compass points (e.g., W, NW, N)
- Reported directions represented gross observations rather than actual measurements

The digitized questionnaire responses, presented in Appendix C, could be used as a database for specific problem areas.

Table 5. Illustration of automated procedure used to calculate prevailing wind direction from potential transport over the snow accumulation season. Data are for Albany, New York, for the record period January 1, 1964 through March 4, 1995.

(1) Direction, D	(2) Q_{upot}	(3) $D*Q_{upot}$	(4) Cumulative $D*Q_{upot}$	(5) Cumulative Q	(6) Prevailing direction	(7) % of total
	-kg/m-	-deg*kg/m-	-deg*kg/m-	-kg/m-	-degrees-	-%-
10	17,186	171,864	171,864	17,186	10.0	1.57
20	10,474	209,475	0	0		
30	4,687	140,606	0	0		
40	2,027	81,078	0	0		
50	846	42,319	0	0		
60	154	9,220	0	0		
70	102	7,171	0	0		
80	232	18,538	0	0		
90	154	13,830	0	0		
100	154	15,367	0	0		
110	307	33,807	0	0		
120	437	52,393	0	0		
130	744	96,713	0	0		
140	7,977	1,116,822	0	0		
150	23,913	3,586,888	3,586,888	23,913	150.0	2.18
160	38,954	6,232,591	9,819,479	62,866	156.2	5.74
170	59,295	10,080,154	19,899,634	122,161	162.9	11.15
180	38,323	6,898,141	26,797,774	160,484	167.0	14.65
190	9,122	1,733,267	0	0		
200	3,056	611,254	0	0		
210	1,054	221,281	0	0		
220	1,207	265,625	0	0		
230	1,642	377,558	0	0		
240	5,381	1,291,502	0	0		
250	12,303	3,075,717	3,075,717	12,303	250.0	1.12
260	23,571	6,128,378	9,204,095	35,874	256.6	3.27
270	82,521	22,280,577	31,484,672	118,394	265.9	10.81
280	147,285	41,239,913	72,724,585	265,680	273.7	24.25
290	231,954	67,266,576	139,991,161	497,633	281.3	45.43
300	204,134	61,240,236	201,231,398	701,767	286.7	64.06
310	102,829	31,877,082	233,108,479	804,597	289.7	73.45
320	29,898	9,567,249	242,675,729	834,494	290.8	76.18
330	7,296	2,407,525	0	0		
340	3,662	1,245,225	0	0		
350	7,083	2,479,164	0	0		
360	15,495	5,578,052	5,578,052	15,495	360.0	1.41
370	17,186	6,358,961	11,937,012	32,681	365.3	2.98
380	10,474	3,980,029	0	0		
390	4,687	1,827,881	0	0		

400	2,027	810,778	0	0		
Total (10-360)	1,095,458					

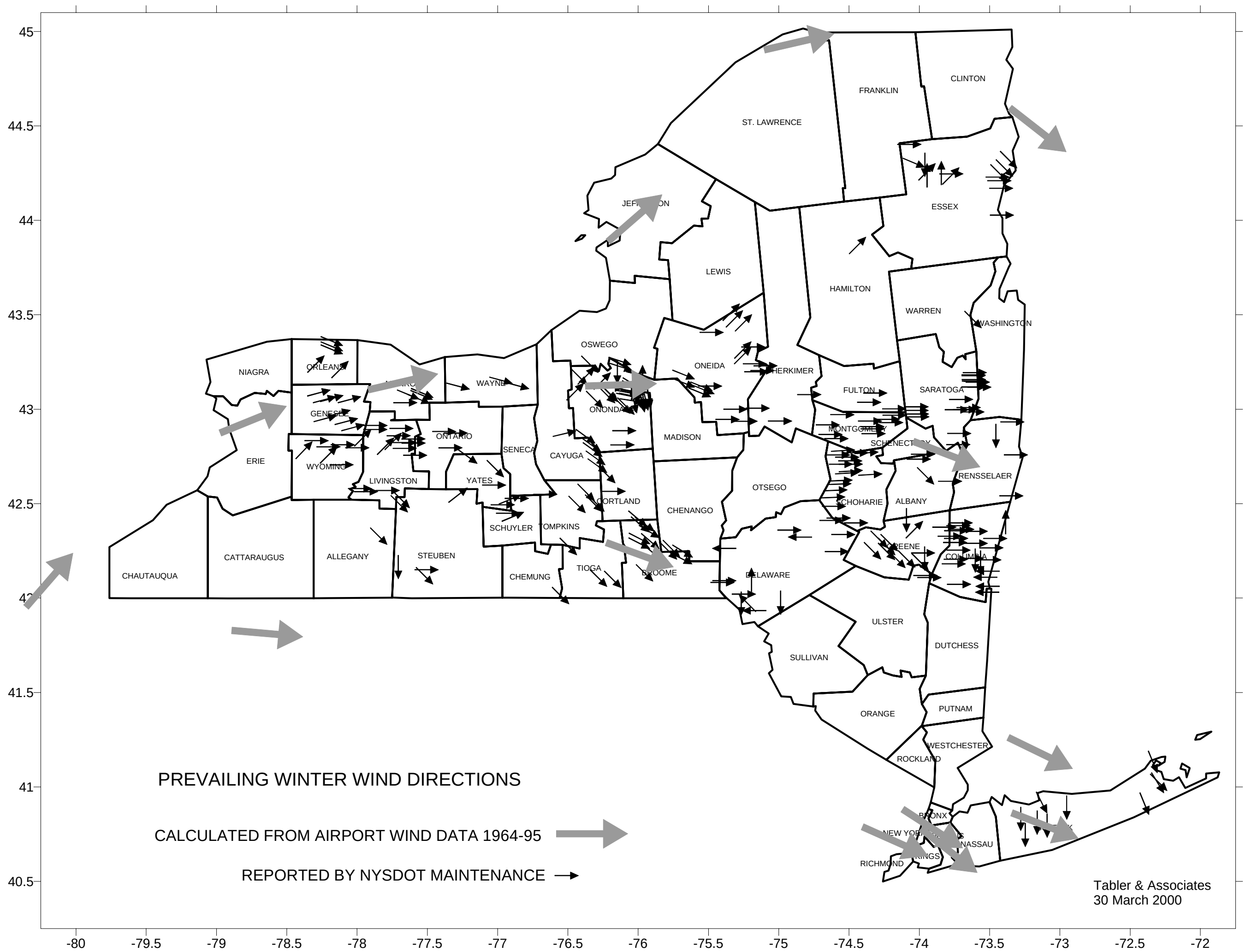

Figure 7. Prevailing directions of snow transport at the stations used for wind analyses, and directions reported by NYSDOT maintenance personnel for specific problem locations.

The regression for directions from the $Q_{upot,AS}$ analysis should be reanalyzed after incorporating additional wind data available from other sources such as the NCDC International Surface Weather Observations. At least 10 years of 36 compass-point wind data are available for the following stations:

Elmira / Corning
Fort Bennett
Geneva
Glens Falls
Hempstead AFB
Newburgh
Plattsburgh, AFB
Niagara Falls
Poughkeepsie
Rome, Griffiss AFB
Stewart AFB
West Hampton Beach
White Plains
Teterboro, NJ

Table 6. Frequency distribution of wind directions reported by NYSDOT maintenance personnel.

Direction	Frequency	Frequency	Cum. Freq.
	-number-	-%-	-%-
10	0	0.0	0
20	0	0.0	0
30	0	0.0	0
40	0	0.0	0
50	0	0.0	0
60	0	0.0	0
70	0	0.0	0
80	0	0.0	0
90	7	2.4	7
100	0	0.0	7
110	0	0.0	7
120	0	0.0	7
130	0	0.0	7
140	1	0.3	8
150	0	0.0	8
160	0	0.0	8
170	0	0.0	8
180	5	1.7	13
190	0	0.0	13
200	0	0.0	13
210	0	0.0	13
220	0	0.0	13
230	19	6.6	32
240	1	0.3	33
250	2	0.7	35
260	9	3.1	44
270	137	47.2	181
280	1	0.3	182
290	10	3.4	192
300	16	5.5	208
310	12	4.1	220
320	44	15.2	264
330	1	0.3	265
340	3	1.0	268
350	3	1.0	271
360	19	6.6	290

SUMMARY OF RESULTS

Snow accumulation season dates:

$$\textbf{Fall Date} = 642.3 - 0.0361 * \textbf{Elev} - 6.922 * \textbf{Lat} \quad (3a)$$

$$\textbf{Spring Date} = -284.8 + 0.0395 * \textbf{Elev} + 8.101 * \textbf{Lat} \quad (3b)$$

where Elev = elevation in meters, Lat = Latitude in degrees (N)

Total annual snowfall, S_T (inches):

TASF grid.dat

Snowfall over snow accumulation season, S_{AS} (inches):

SASSF grid.dat

Ratio of snowfall over accumulation season (S_{AS}) to total annual snowfall (S_T):

$$\mathbf{S_{AS} / S_T = -3.19 + 0.00028 * Elev + 0.0841 * Lat + 0.0034 * Lon} \quad (6)$$

where *Elev* and *Lat* are as previously defined, and *Lon* is degrees west longitude (positive)

Snowfall water-equivalent, S_{WE}:

$$\mathbf{S_{WE} = 0.1 * S}$$

Snow relocation coefficient, C_R:

$$\mathbf{C_R = Q_{upot,BS} / Q_{spot} = 0.17}$$

Snow transport over snow accumulation season, Q (kg/m):

$$\mathbf{Q = 1500(0.17)(S_{we,AS})(1 - 0.14^{F/3000})} \quad (12)$$

where snowfall water-equivalent ($S_{we,AS}$) is in millimeters, and fetch (F) is in meters

Prevailing direction of snow transport (degrees True North azimuth):

$$\mathbf{Direction = 987 - 9.42 * Lon} \quad (14)$$

REFERENCES CITED

Abramowitz, M. and I. Stegun. 1972. Handbook of Mathematical Functions. Dover Publications, New York.

Changery, M. J. 1978. National wind data index: Final Report. U. S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data and Information Service, National Climatic Center, Asheville, North Carolina 28801, Report No. HCO/T1041-01, UC-60, prepared for U. S. Department of Energy, Division of Solar Technology. 245 pages.

Cressie, N. A. C. 1990. The origins of Kriging. Mathematical Geology, V. 22. Pp. 239-252.

Golden Software, Inc. 1999. Surfer® 7 Users Guide. Golden, Colorado. 619 pages.

Pack, A. B. 1972. Climate of New York. See listing under States Department of Commerce.

Sutton, O. G. 1953. Micrometeorology. McGraw-Hill Book Co., Inc., New York. 333 pages

Tabler, R. D. 1975. Estimating the transport and evaporation of blowing snow. Symposium on Snow Management on the Great Plains (Bismarck, N. Dak.; July 1975) Proceedings, Great Plains Agricultural Council Publication 73: 85-104.

Tabler, R. D. 1982. Frequency distribution of annual peak water-equivalent on Wyoming snow courses. Western Snow Conference (Reno, Nev.; April 20-23, 1982) Proceedings 50: 139-148.

Tabler, R. D. 1988. Estimating dates of the snow accumulation season. Western Snow Conference (Kalispell, Montana; April 19-21, 1988) Proceedings 56:35-42.

Tabler, R. D. 1991. Snow transport as a function of wind speed and height. *In:* Cold Regions Engineering. Proceedings, Cold Regions Sixth International Specialty Conference TCCP/ASCE (Feb. 26-28, 1991; West Lebanon, New Hampshire): pp. 729-738.

Tabler, R. D. 1994a. Design Guidelines for the Control of Blowing and Drifting Snow. Strategic Highway Research Program, Publication SHRP-H-381, National Research Council, Washington, D.C. 364 pp.

Tabler, R. D. 1994b. US Route 19 Passive Snow Control: Design Criteria Evaluation. Report prepared for Region 5, New York State Department of Transportation. 38 pages.

Tabler, R. D. 1997. Computer-Aided Design of Drift Control Measures. Final Report, Research Agreement #47608, Research Project #FHWA-WY-97/02. 122 pp.

Tabler, R. D., C. S. Benson, B. W. Santana, and P. Ganguly. 1990. Estimating snow transport from wind speed records: Estimates versus measurements at Prudhoe Bay, Alaska. Western Snow Conference Proceedings 58: 61-72.

Tabler, R. D., N. H. Berg, D. Trabant, H. Santeford, and P. A. Rechard. 1990. Measurement and evaluation of winter precipitation. Cold Regions Hydrology and Hydraulics, ASCE Technical Council on Cold Regions Engineering Monograph. pp. 95-145

United States Department of Commerce. 1972. Climate of New York, by A. B. Pack. Climatography of the United States No. 60-30, Climate of the States. National Oceanic and Atmospheric Administration, Environmental Data Services, Silver Spring, Maryland. 29 pages.