On Sudbury-Area Wind Speeds—A Tale of Forest Regeneration

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ABSTRACT

A 34% reduction in 10-m wind speeds at Sudbury Airport in Ontario, Canada, over the period 1975–95 appears to be a result of significant changes in the surface roughness of the surrounding area that are due to land restoration and reforestation following historical environmental damage caused by high sulfur dioxide and other industrial emissions. Neither 850-hPa winds extracted from the NCEP–NCAR reanalysis database nor wind measurements at meteorological stations 200 km to the north and 120 km to the east of Sudbury show the same decrease. To assess these changes in observed wind speed quantitatively, geostrophic drag laws were employed to illustrate potential changes in near-surface wind speeds in areas surrounding the airport. A model of the internal boundary layer flow adjustment associated with changes in the surface roughness length between the surroundings and the grass or snow surface of the airport was then applied to compute expected annual average wind speeds at the airport site itself. The estimates obtained with this relatively simple procedure match the observations and confirm that reforestation is likely the major cause of the reduced wind speeds. This finding bears economic, social, and ecological importance, because it will influence wind energy potential, wind loads on structures, wind chill, and home heating costs through to the biology of small- to medium-sized lakes.

1. Introduction

The city of Sudbury (46°30′N, 81°00′W), Ontario, Canada, has undergone a remarkable transformation over the past 30 years. Located upon the mineral- and metal-rich Canadian Shield, the Sudbury area has been continuously mined for nickel, copper, and iron since the late nineteenth century. By the 1970s, over 1×10^8 t of sulfur dioxide (SO_2) from open roast beds and, later, smelters had stripped the regional mixed coniferous–deciduous forest type, leaving over 200 km^2 of land bare and 800 km^2 of land semibare (Gunn et al. 1995; Winterhalder 1996), extending up to 30 km north and 20 km south of Sudbury (Fig. 1). Remaining forested areas shifted in species composition during this time period from red- (*Pinus resinosa*) and white-pine- (*P. strobus*) dominated stands to more open-canopy, early-successional species, including white birch (*Betula papyrifera*) and trembling aspen (*Populus tremuloides*) (Pitbaldo and Amiro 1982; Jackson et al. 2000). Similar patterns in deforestation have been observed near other point sources of SO_2 emissions—for example, north of Sault Ste. Marie, Ontario, Canada (Gorham and Gordon 1963).

In response to a progressively degraded landscape,

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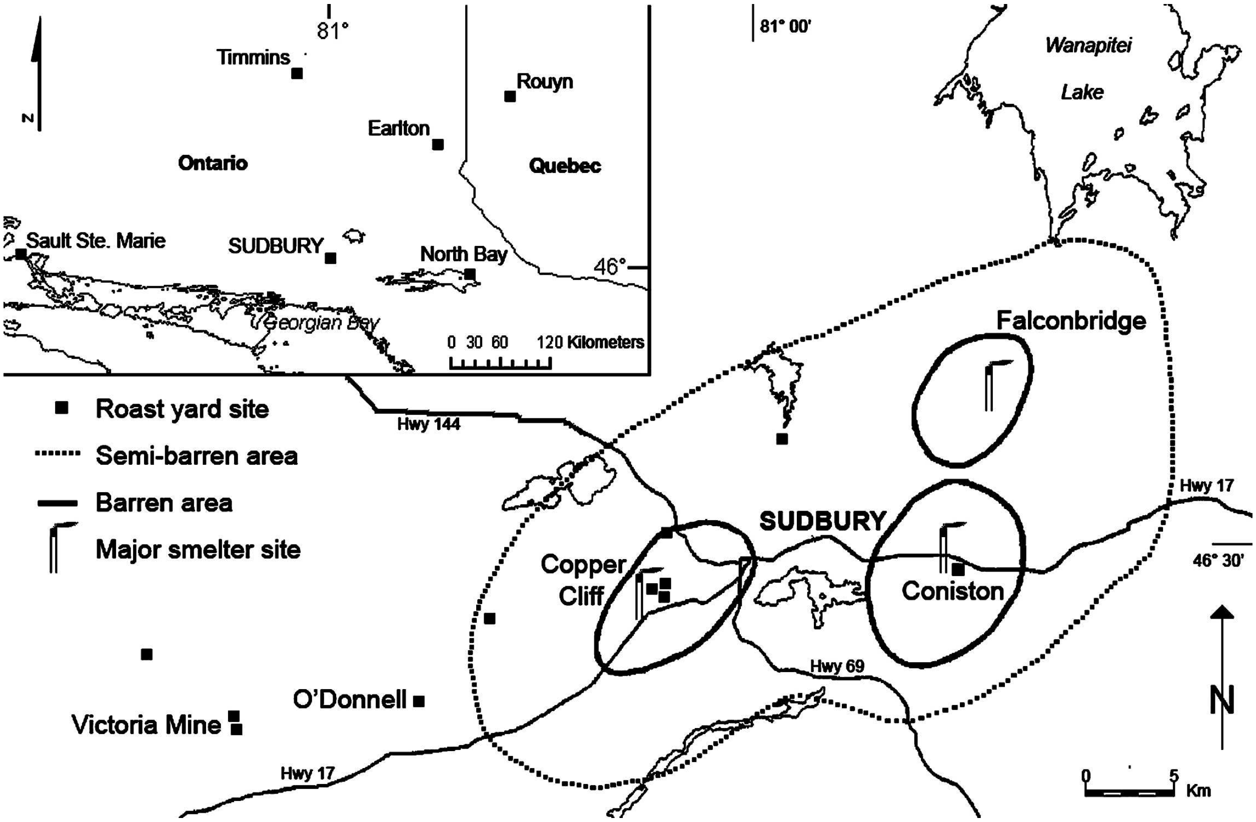

FIG. 1. Location of the major sites of roasting and smelting activity in the Sudbury area. The areas of vegetation damage are based on 1970 aerial photography (adapted from Gunn et al. 1995).

stringent regulations were enacted to reduce SO_2 emissions, and restoration efforts were initiated during the 1970s and early 1980s (Lautenbach 1987; Winterhalder 1996). A 90% decrease in SO_2 emissions since the 1960s (Gunn et al. 1995; Keller et al. 2007) and the planting of over 8 million trees (VETAC 2005) have contributed to recent, albeit slow, recovery (McCall et al. 1995). However, as Lautenbach et al. (1995) note, the land restoration program of the city of Sudbury and its neighbors in the regional municipality has been remarkably successful in reforesting much of the area and transforming the city of Sudbury (Fig. 2).

The effect of deforestation on wind speeds has been widely studied (Chen et al. 1995; Brosofske et al. 1997; Steedman and Kushneriuk, 2000; Hoffmann et al. 2002), but the influence of a maturing urban forest on wind speeds is relatively undocumented, despite economic and social implications (e.g., reductions in wind energy potential and in winter wind chill). Related studies on changes resulting from urbanization are reviewed by Oke (2004). Associated, we assume, in part with the declining wind speeds, there have been major changes in the summer thermal regime of nearby lakes as a result of reduced mixing and shallower thermoclines (Tanentzap 2006). Here, we tested whether increases in regional surface roughness, attributable to the planting and growth of over 8 million trees, could account for an observed decrease of more than 30% in mean annual wind speed between 1975 and 1995 recorded at Sudbury Airport (46°37′N, 80°48′W), approximately 20 km northeast of the city.

2. Study area and regional trends in wind speed

Sudbury, Ontario, is located within the cool summer subtype of the humid continental climate using the Koppen classification scheme (Dfc). Mean annual air temperature recorded at Sudbury Airport from 1970 to 2005 was 3.8°C, with monthly means of −13.6° and 19.1°C in January and July, respectively. Total annual precipitation averaged 907.3 mm over this period. The topography of the Sudbury area is generally flat, especially near the airport. (This can be seen from detailed contour maps and is illustrated in the photographs in Fig. 4, described below.) There are pothole lakes east-northeast of the airport, and there is rolling terrain, as

FIG. 2. Sample recovery pictures that allow comparison of (left) 1979 with (right) 2001 (Sudbury Soils Study 2006).

in Fig. 2, but slopes are moderate (mostly less than 5% near the airport), and topography is unlikely to affect the geostrophic drag relationship [Eq. (1)] used later in the paper.

Wind speed and direction, available from Sudbury Airport since its opening in 1954, are shown from 1970 to 2001 in Fig. 3. Annual average speeds reached a peak (6.5 m s^{-1}) in 1956 and declined slightly after that to values of around 5.5 m s^{-1} in the early 1970s. Sudbury Airport annual mean wind speeds have, however, been below 4 m s^{-1} since 1988—a decline of almost 40% over 32 yr. A 34% decrease in annual averaged wind speed took place between 1975 and 1995 (Fig. 3) during the period in which significant ecological restoration and reforestation were being undertaken. Month-by-month analyses of the Sudbury Airport data show wind speed reductions in all months, with the largest relative reductions in summer, when the deciduous trees (aspen and birch) would be in leaf. Regression-line fits for each season give 34%–35% reductions in autumn, winter, and spring but a 46% reduction in summer (June, July, August). Note that the strongest wind speeds occur in March and April and that minima are in July and August.

Sudbury stands out as having the most dramatic change of several regional stations. There was little or no significant decline in wind speeds at stations 200 km to the north (Timmins) and 120 km to the east (North Bay), as shown in Fig. 3. Earlton, to the northeast, also shows little change, whereas Rouyn, farther northeast and near the Noranda smelter, has a significant decline in the late 1970s. At Sault Ste. Marie, 250 km to the west, there was considerable variability and some indication of a decline, as shown in Fig. 3. However, significant reductions based on fitted Sen's slopes (see Gilbert 1987) for 1973–2001 were the largest at Sudbury (Sen's slope = -0.060 m s^{-1} yr^{-1}), in comparison with Sault Ste. Marie (Sen's slope = -0.043 m s^{-1} yr^{-1}), Earlton (Sen's slope = 0.013 m s^{-1} yr^{-1}), and Rouyn (Sen's slope = -0.013 m s^{-1} yr^{-1}). We attribute this decline at Sudbury to ecological changes linked to the huge reductions in SO_2 emissions plus the extensive reforestation efforts undertaken by the city of Sudbury and the neighboring region.

To confirm further that these effects were associated

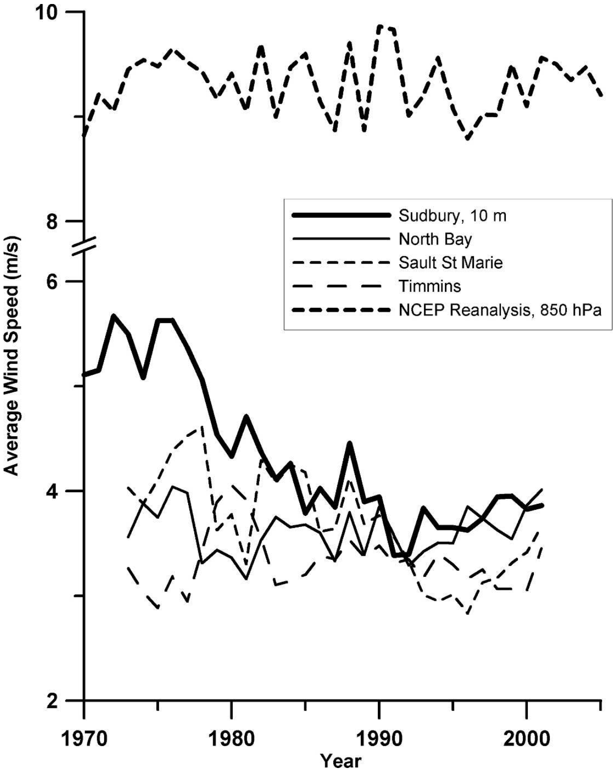

FIG. 3. Annual average wind speeds for Sudbury Airport and three nearby Environment Canada stations (1973–2001), and annual averaged NCEP–NCAR reanalysis wind speeds for 850 hPa.

with local changes rather than any broader-scale reductions in wind speed, we made use of National Centers for Environmenal Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data to investigate average 850-hPa wind speeds in the region. (NCEP–NCAR data are in the public domain and were provided by the National Oceanic and Atmospheric Administration–Cooperative Institute for Research in Environmental Sciences Climate Diagnostics Center on their Web site at http://www.cdc.noaa.gov/). These data indicate minimal changes in wind speed and no long-term trend. We computed annual average mean wind speeds at 850 hPa in a 3° latitude and 3° longitude region centered on Sudbury (also shown in Fig. 3). The 850-hPa level is at approximately 1450 m above sea level, or 1100 m above ground, which provides a reasonable estimate of the gradient or geostrophic wind above the boundary layer. These plots, and other reanalysis data, indicate essentially no change over the 30-yr period from 1970 to 2000. For the Sudbury area, we estimate the long-term geostrophic wind speed as 9.3 m s^{-1}.

3. Planetary boundary layer relationships between upper-level and surface winds

Relationships between the geostrophic wind U_g above the boundary layer at heights of order 1 km above the ground and near-surface wind speed and direction at, say, height above ground $z = 10$ m can be established for neutrally stratified, barotropic situations, based on the geostrophic drag laws and Rossby number similarity. These ideas and extensions to nonneutral and baroclinic situations are extensively reviewed in the textbook by Garratt (1994, chapter 3). For this analysis, we assume that yearly average wind speed relationships correspond approximately to the ideal neutral, barotropic case and that these provide some guidance on the relationship between the surface and geostrophic winds. The relationships vary with the roughness Rossby number, $\mathrm{Ro} = G/(|f|z_0)$, where $G = |U_g|$ is the geostrophic wind speed, based on the surface pressure gradient, and is assumed to be constant throughout the boundary layer; f is the Coriolis parameter; and z_0 is the surface roughness length.

The geostrophic drag laws predict $u_*/|U_g|$ as a function of Ro, and, for neutral conditions, they can be written in the form

$$(u_*/G)^2 = \kappa^2 \Bigg/ \left\{\left[\ln\left(\frac{u_*}{|f|z_0}\right) - A\right]^2 + B^2\right\}, \quad (1)$$

where A and B are, in principle, universal constants, κ is the von Kármán constant with a value of 0.4, and u_* is the friction velocity. We use values of $A = 2$ and $B = 4$ in the calculations below. [Note that different authors use interchanged symbols A and B. The usage here follows that employed by Garratt (1994) but is opposite to that found in Walmsley et al. (1989) and the Guidelines proprietary software (Salmon 1999).] For a given value of G, and for known f and z_0, Eq. (1) can be solved iteratively—for example by Newton's method—to obtain u_*. We can then assume a logarithmic velocity profile of

$$U = (u_*/\kappa)\ln[(z + z_0)/z_0] \quad (2)$$

written in the form that gives $U = 0$ on $z = 0$ to predict the 10-m wind speed. Equation (2) applies in the near-surface layer (say $z < 50$ m) for near-neutral stratification. For very rough surfaces, such as a forest, one can also introduce the concept of a displacement height or zero-plane displacement d, which is often considered to be about $2h_c/3$, where h_c is the canopy height (Garratt 1994). We do not formally include this here but consider all heights to be measured upward from the adjusted zero plane.

In principle, we could extend the modeling concept to nonneutral conditions using Monin–Obukhov similarity laws in the surface layer and allowing A and B to be functions of a stability parameter, but for now we simply use values appropriate to near-neutral conditions. We can note that the stability parameters [the Obukhov length L for the constant flux layer, and $\mu_i = h/L$, where h is a boundary layer depth, or $\mu_0 = \kappa u_*/(fL)$] used in the geostrophic drag laws will be hard to estimate from the data that we have available. In addition, even with carefully selected data, as in Arya (1975), the relationships $A(\mu_0)$ and $B(\mu_0)$ show considerable scatter and uncertainty. Thus we have taken the view that, over a rough surface, near-neutral conditions will predominate in the lowest layers and that, for the geostrophic drag laws, increased values (relative to neutral stratification) of u_*/G in unstable, daytime conditions will be offset by reduced values at night under stable stratification.

Sudbury Airport is at latitude 46.5°N, and the corresponding Coriolis parameter is $f = 1.058 \times 10^{-4}$ s^{-1}. The other parameter that we need is the roughness length z_0, and it is the change in z_0 over time that makes the Sudbury story interesting. Values of z_0 for natural surfaces typically range from 10^{-4} m over water or smooth ice or snow, through 10^{-2} m over short grass or bare soil surfaces, to 1 m or so over forests or urban areas. Although the variation is large, it is in effect the logarithm of z_0 that really matters and, for natural surfaces, $\log_{10}z_0$ generally only varies from -4 to 0. It is

TABLE 1. 10-m wind speeds (m s^{-1}) for neutral barotropic conditions based on Eq. (1) for Sudbury Airport (46.5°N).

G (m s^{-1})	Roughness length (m)						
	10^{-4}	10^{-3}	10^{-2}	5×10^{-2}	10^{-1}	5×10^{-1}	1
5	3.87	3.59	3.19	2.80	2.59	1.96	1.62
10	7.42	6.85	6.05	5.27	4.86	3.66	3.02
15	10.87	10.01	8.80	7.64	7.04	5.29	4.35
20	14.20	13.05	11.45	9.96	9.13	6.87	5.61
9.3	6.92	6.40	5.65	4.93	4.55	3.43	2.82

our contention that the significant decrease in wind speed observed at Sudbury Airport over the past 30 yr has been caused by an increase in the roughness length of the surrounding countryside from a value of about 0.05 m when there were few trees to a current value of 0.5–1.0 m with the regenerated forest surroundings.

The roughness length appropriate to the airport itself will not have changed significantly during this time, and we will also need to take account of the internal boundary layer and any sheltering effects of buildings on the airfield in the vicinity of the anemometer. In addition, there will be summer/winter differences caused by snow cover and vegetation changes and differences in the effects of thermal stratification with the seasons.

To give a simple example of differences in 10-m wind speeds over different surfaces for the same geostrophic wind speed, we have constructed Table 1 for a location in the Sudbury area (at 46.5°N). Note that increasing roughness lengths by a factor 10 (from 0.05 to 0.5 m, which are not unreasonable values for the change from semibare or bare soil to forest) leads to a 30% (for G = 5 m s^{-1}) to 31% (for G = 20 m s^{-1}) decrease in the 10-m wind speed. It is important to note that this ratio is relatively independent of G for the values used in Table 1 because this result supports our use of an annual average value of G (9.3 m s^{-1}) in the later calculations.

In the following sections we take account of the details of the Sudbury Airport siting and relate the climatological conditions there to the geostrophic wind climatological conditions from the NCEP–NCAR reanalysis data.

4. Local effects and application of GLW

As at most airports, the anemometer at Sudbury Airport is located in a level area with short grass and a corresponding surface roughness length of order 0.01 m. In winter, there is snow cover and, with no vegetation protruding through the snow (Fig. 4), the effective roughness length could be of order 0.001–0.0001 m.

Measurements made at the anemometer are thus not the same as would be made at a comparable height over the surrounding area but will be higher as a result of the flow accelerating within the internal boundary layer over the smoother airport surface. The concept of an internal boundary layer (IBL) associated with flow over an abrupt change in surface roughness (Fig. 5) was established by Elliott (1958) and extended by many authors [see Garratt (1994) for a discussion]. The depth δ of the IBL within which the flow is adjusting to the new, downwind surface roughness will increase with distance x downwind of the roughness change. In the simplest models, following Panofsky and Townsend (1964) and others, we can work within the framework of a "surface layer." This is generally appropriate for IBL heights up to about 150 m and downwind distances up to about 2 km. We assume logarithmic velocity profiles within and above $\delta(x)$, corresponding to the upwind and downwind values of the roughness length: z_{0u} and z_{0d}. For a number of different empirical prediction formulas for $\delta(x)$, see Savelyev and Taylor (2005). Here we use the Panofsky–Dutton formula, coded within the Guidelines for Windows (GLW) software and based on Walmsley et al. (1989). GLW, developed as a user-friendly software package by the Zephyr North company (see www.ZephyrNorth.com), allows for calculation of the effects of both topography (hills, ridges, escarpments, or valleys) and roughness change on near-surface wind speeds.

The idealized situation that we will consider assumes no significant topography and a step change from the surrounding wooded area with roughness length z_{0u} to the airfield with roughness length z_{0d}. Author Salmon conducted a survey of the airport in 2002. Average tree heights at that time were estimated at 4.5 m. In addition to the transition from the surrounding forest to the airfield there is the possibility of making sheltering corrections for effects of any upwind obstacles or isolated lines of trees using the model proposed by Taylor and Salmon (1993) and implemented in Zephyr North's Shelter Correction (ShelCorr) software. The airport anemometer is, however, situated about 700 m from the nearest airport buildings, and sheltering effects were computed to be negligible (<1% in any 22.5° sector).

To estimate the local increases in wind speed associated with the change from forest or the prereforestation scrub to grass or snow on the airfield we used the GLW implementation of Walmsley et al.'s (1989) guidelines, assuming flat terrain and various values of roughness length for the airport surroundings (semibarren and forest) and area (grass and snow). The speedup in 10-m wind associated with the change in roughness was then calculated as a function of upwind distance between the anemometer and the roughness change. Figure 6, based on 2003 aerial photographs available from the Sudbury

FIG. 4. (left) The Sudbury Airport anemometer, and (right) a view from the anemometer tower toward the northwest (25 Mar 2002).

Web site (www.city.greatersudbury.on.ca), was used to estimate the airport–forest boundary distances given in Table 2. We have also studied aerial photographs from 1975 and see no significant change in these boundary distances with time.

The GLW modeled speedup ratio estimates (Table 2) are based on the increases in 10-m wind speed between a location upwind of the transition to airport grass or bare snow and the airport anemometer location. These estimates assume neutral thermal stratification and account only for the effects of roughness change as the flow accelerates within the internal boundary layer. They are clearly dependent on the assumed values for all roughness lengths, and two sets of values are given for the estimated forest roughness length. Our first estimate was 0.5 m based on 0.1 × tree height, but, as is seen below, there is a better match with observations if we increase this value to 1.0 m. Note that this was the only change made from our initial estimates. Both 0.5 and 1.0 m are within the range of values generally estimated for a pine or coniferous forest (0.3–4 m; see Garratt 1994). Winter speedup values over the snow-covered airfield are generally higher than over the summer grass, the exception being at short fetches (<600 m) when the internal boundary layer depth over the snow surface is relatively shallow. In the case in which the fetch is 160 m for winds from 270° the internal boundary layer depth over the snow surface is less than the measurement height of 10 m, and so no velocity change occurs.

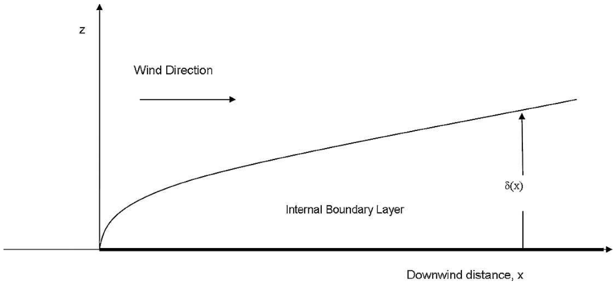

FIG. 5. Schematic diagram of the internal boundary layer downwind of a step change in surface roughness from z_{0u} to z_{0d}.

FIG. 6. Aerial photo of Sudbury Airport (http://www.greatersudbury.ca/pubapps/ortho/) from 2003. The approximate anemometer location is indicated by the small black triangle. The length of the main (NNE–SSW) runway is 2100 m.

If we assume that the semibarren area was large enough for the near-surface winds to come into equilibrium with the geostrophic wind above that surface and if we assume an annual average geostrophic wind speed of 9.3 m s^{-1} (from the NCEP–NCAR reanalysis data), then we can estimate annual average 10-m wind speed at the airport, as indicated in Table 3. To do this, we have taken into account the frequency of winds from different directions, split into 16 bands, and have used the roughness change data from Table 2. We assumed the same directional distribution for both the 1973–75 and 1999–2001 periods. Directional frequency values given in Table 2 are an average for the two periods; differences between the frequencies in each 22.5° band between the time periods were all less than 1.7% and were less than 1% for all but two direction bands.

In our view, Table 3 confirms our hypothesis that the explanation for reductions in the observed wind speeds at Sudbury Airport over the past 20–30 years can be explained both qualitatively and, to some extent, quantitatively by an analysis of changes in geostrophic drag resulting from the reforestation of an extensive area around greater Sudbury and a detailed analysis of wind speed adjustments within internal boundary layers at the airport site itself. It suggests that the wind speed reductions at 10 m above the zero-plane adjustment are of order 43% as compared with the 28% reduction observed at the airport between these two periods. This difference may be significant for other studies, including those on the effects of wind speeds over small lakes in the Sudbury area (Tanentzap 2006).

5. Conclusions

Annual average wind speeds in the Sudbury area declined steadily from 1975 to 1995 while average 850-hPa wind speeds remained approximately unchanged. These reductions appear to be linked to land recovery, restoration, and reforestation. Models of flow over sur-

TABLE 2. Speedup calculations for the airport anemometer site based on reduced surface roughness relative to surrounding area. Here S indicates summer and W indicates winter.

Center of 22.5° sector	Frequency (%) from this direction	Distance from anemometer to roughness change (m)	Speedup factor					
			1973: semibarren ($z_0 = 0.05$ m)		2001: 5-m trees ($z_0 = 0.5$ m)		2001: 5-m trees ($z_0 = 1.0$ m)	
			S	W	S	W	S	W
0	7.8	600	1.05	1.09	1.22	1.23	1.34	1.33
22.5	8.3	780	1.06	1.10	1.25	1.27	1.38	1.39
45	7.1	2200	1.08	1.16	1.35	1.43	1.54	1.62
67.5	4.0	1900	1.08	1.16	1.34	1.41	1.52	1.59
90	2.8	1000	1.06	1.12	1.28	1.31	1.42	1.45
112.5	3.2	1000	1.06	1.12	1.28	1.31	1.42	1.45
135	4.2	1000	1.06	1.12	1.28	1.31	1.42	1.45
157.5	5.4	1300	1.07	1.13	1.30	1.36	1.47	1.51
180	6.6	2000	1.08	1.16	1.35	1.42	1.53	1.60
202.5	8.4	900	1.06	1.11	1.27	1.30	1.41	1.43
225	9.3	600	1.05	1.09	1.22	1.23	1.34	1.33
247.5	8.3	200	1.02	1.01	1.08	1.02	1.12	1.03
270	5.3	160	1.01	1.00*	1.05	1.00*	1.07	1.00*
292.5	5.8	200	1.02	1.01	1.08	1.02	1.12	1.03
315	5.7	300	1.03	1.04	1.05	1.11	1.21	1.15
337.5	7.9	600	1.05	1.09	1.22	1.23	1.34	1.33
		Seasonal	1.05	1.09	1.22	1.24	1.35	1.35
		Annual	1.07		1.23		1.35	

* Value is 1.00 at 10 m because IBL depth at this fetch is <10 m. Annual values are based on 4 months of winter with snow cover. For summer, we take $z_0 = 0.01$ m; for winter, $z_0 = 0.0005$ m.

faces of different roughness length and internal boundary layer models give a satisfactory explanation for the changes. There are a number of consequences of the reductions in wind speed in the area.

One impact is on the wind energy potential. The 10-m mean wind speed map, produced by Environment Canada based on wind data for 1967–76 (Walmsley and Morris 1992), shows an interesting excursion of the 15 km h^{-1} (4.2 m s^{-1}) isotach away from the northern shore of Georgian Bay to include the Sudbury area. This was presumably based on the relatively high wind speeds reported at Sudbury Airport for that period and would have been appropriate for that period of time. In current times, however, reforestation has reduced the wind speed, and the 15 km h^{-1} contour should follow the shoreline. The recently released Ontario wind atlas (which was available online at http://www.ontariowindatlas.ca/) indicates 10-m wind speeds of around 2.6 m s^{-1} for the Sudbury Airport area. This value is lower than was observed at the airport but is consistent with speeds expected in the surrounding area (cf. Table 1 with $G = 9.3$ m s^{-1} and $z_0 = 1$ m). Our conclusion is that the map based on the 1967–76 data is no longer valid and that our simple estimates based on NCEP–NCAR reanalyses and geostrophic drag relationships are consistent with values from the more recent wind atlases for this area.

On the positive side, there are reduced wind loads on structures, but the presence of trees near power lines can have an adverse impact, because local power outages are often caused by trees falling across power lines. Blizzard conditions and drifting and blowing snow can be hazards to transportation, and reduced wind speeds will have a beneficial effect in reducing the frequency of these events. Wind chill and heat loss from buildings should also be reduced.

There are many lakes in the Sudbury area. Limnological studies have found that changes in local wind speeds influence 1) lake thermal properties and subse-

TABLE 3. Summary table of annual 10-m wind speeds (m s^{-1}) at Sudbury Airport: estimates and observations. Rows labeled "a" correspond to a forest roughness length of 0.5 m; the "b" rows correspond to a forest roughness length of 1 m. Ratios are relative to the 1973–75 values.

Years	Model estimates ($U_g = 9.3$ m s^{-1})		Airport obs (m s^{-1}; 3-yr avg)
	Over surroundings	At airport anemometer	
1973–75	4.93	5.28	5.40
1999–2001a	3.43	4.22	3.87
1999–2001b	2.82	3.81	
Ratio for a	0.70	0.80	0.72
Ratio for b	0.57	0.72	

quently pelagic biota (France 1997; Steedman and Kushneriuk 2000), 2) aquatic food web structure through phytoplankton resuspension dynamics (Cloern 1987; Arfi and Bouvy 1995; Schelske et al. 1995; Ogilvie and Mitchell 1998), and 3) water quality through nutrient (in particular, phosphorus) release from sediment (Sondergaard et al. 1992; Kleeberg and Dudel 1997). A detailed study showing wind speed effects on Clearwater Lake in the Sudbury area is reported by Tanentzap (2006).

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