# Projecting Mountain Top Wind Profiles based on Observations at Mount Sumanik, Yukon Territory,
**(Preliminary Report for Review)**

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## Introduction

In wind energy assessments we often need to estimate an average wind speed at a higher elevation above ground level (a.g.l., e.g. 30 or 40 m) from an existing lower anemometer height (e.g. 3 – 20 m). This requires some rule that allows us to make that projection.

We cannot define a vertical wind profile that is universal for all mountain top measurements because it depends on several factors such as atmospheric stability and the complexity of the terrain.

In this study we provide some rough guideline based on data measured on Mount Sumanik in July 1999. We assume that the atmosphere is neutral and that the profile depends on orientation of the hill to the wind direction and the location of the station on that hill.

## Sumanik

To visualise what a typical vertical profile of horizontal wind speed looks like we visit Station B on Mount Sumanik and observe the vertical profile measured in July 1999.

The Sumanik B station is located where the X marks the spot in Figure 1. Note the orientation of the mountain and the three wind directions observed during this period.

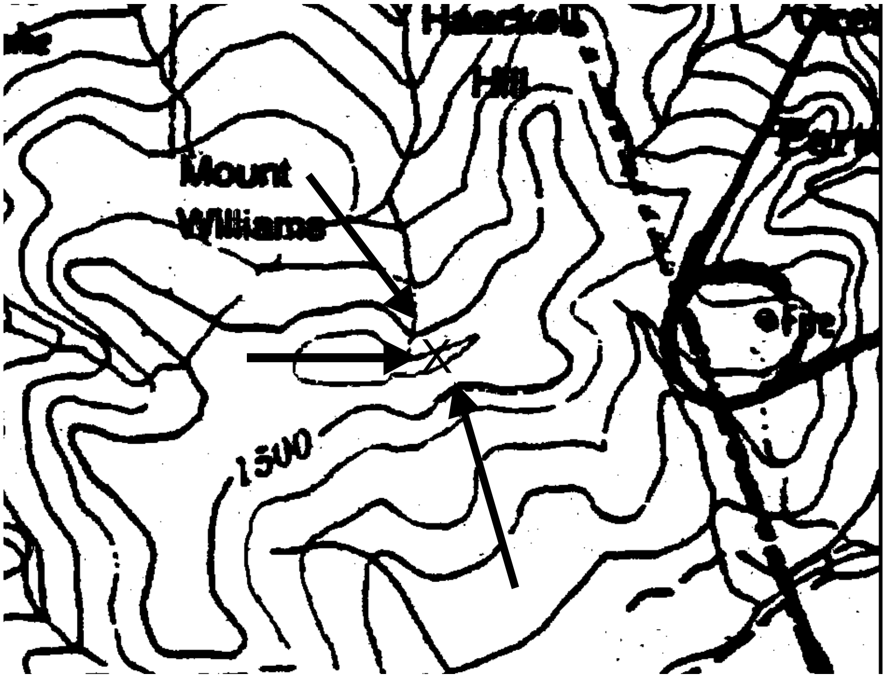


**Figure 1 - The X marks the approximate location of the station on Mount Sumanik. The main wind directions in this case study are marked as arrows from the SSE, W, and NW.**

The data was measured from six NRG Maximum-40 anemometers located at 0.75, 1.5, 3, 6, 12, and 23 m above ground level (a.g.l.) on a 26-m high, 10-cm diameter, guyed tubular tower. The anemometers were held on brackets that extended approximately one meter from the tower, oriented towards the SSE direction. The anemometers had previously been calibrated at the Haeckel Hill research station earlier during the summer, 1999.

The measurements were taken at one-second intervals and averaged at 10-minute intervals. The three main profiles are based on an averaging of seven groups of four 10-minute intervals. Each group was extraction at times when the wind was above 5 m/s and the direction closely matched one of the main directions: NW, W and SSE. The study period was from Julian day 202 to 209, eight days near the end of July 1999. All wind in this case study speeds are normalised to the anemometer at 23 m in order to cancel out the different wind speeds in each group.

The vertical profile of the wind speed from each of the three directions is shown in

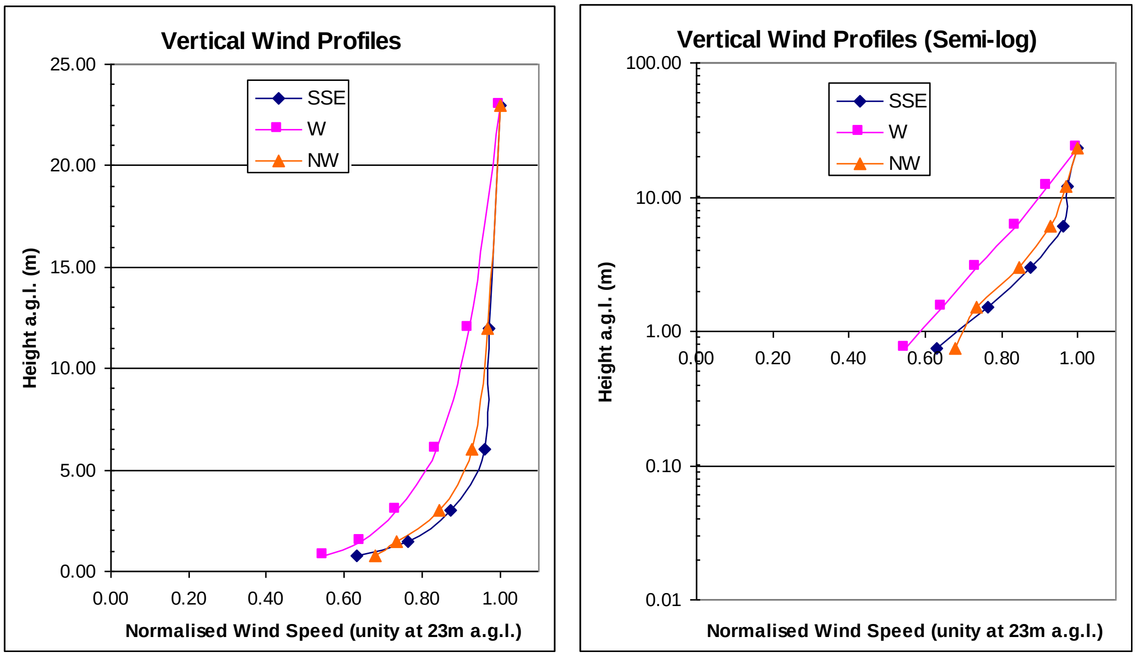


Figure 2 below. The profile for the wind from the W-direction represents a relatively flat terrain; the wind flow follows a relatively level ridge before passing station B.

The other two profiles, from the SSE and the NW are wind flows that are perpendicular to the ridge; that is, the wind was driven up a slope before passing the station. As these two profiles show, there is an accelerated wind effect that is more prominent in the range 1 to 10 m a.g.l. Note that the station is closer to the SSE side of the ridge and shows a higher speed-up then the profile from the NW direction.

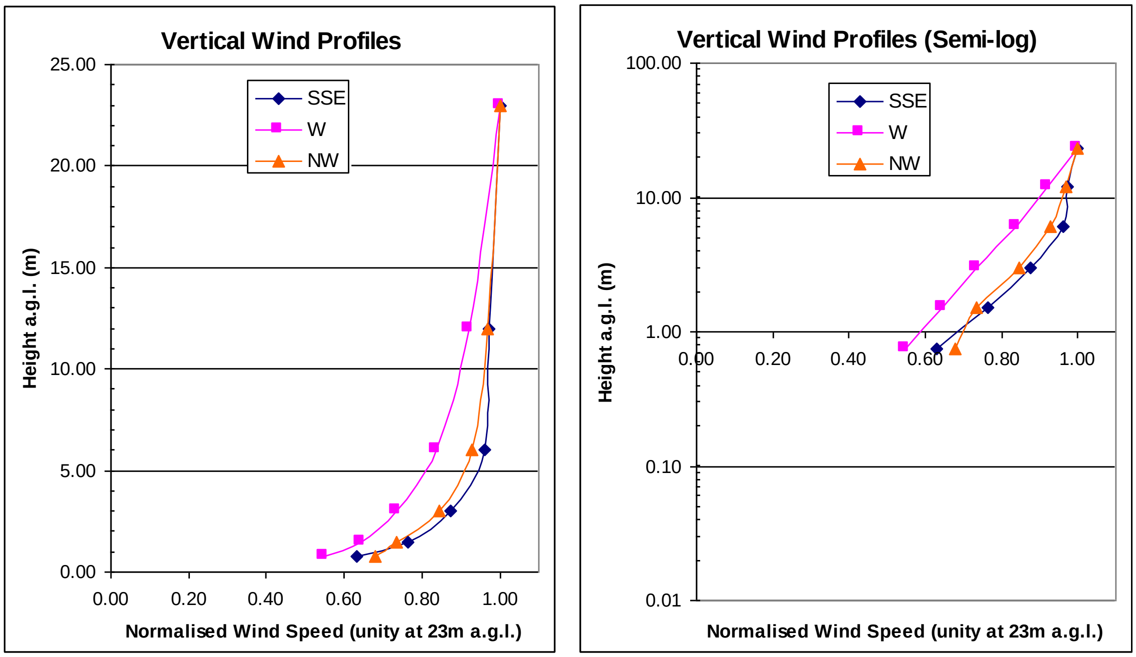


**Figure 2 - The vertical profile of three main wind directions observed at station B during the July 1999 study period. The right hand graph has the height in logarithmic scale. Note that the SSE and the NW winds are perpendicular to the ridge and there show the near ground speed-up effect. The profile for the West is near logarithmic and is representative of flat terrain wind profile as will be shown later.**

## Analytical projection

The are two equations that are commonly sited in wind related literature. These equations are used to fit wind profiles over relatively flat terrain. The first is a power law equation and is shown as:

$$\bar{u}_2 = \bar{u}_1 \left( \frac{h_2}{h_1} \right)^{\alpha} \qquad (1)$$

The time-average speed $\bar{u}_i$ (where *i* is 1,2… taken at level a.g.l.) is measure at height $h_i$ on a tower. The power coefficient $\alpha = 0.14$ was found by using measured speeds at several elevations on Sumanik. This best-fit value matches Equation (1) to the W-direction wind which is representative of flat terrain and is shown in Figure 3 as alpha. Note that the profile for Equation deviates from the measured profile at below 5 m a.g.l.

The second equation is a logarithmic equation that looks like:

$$\bar{u} = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_o}\right) \qquad (2)$$

where $\kappa$ is the Von Karman constant and usually has the value 0.4. The friction velocity $u_*$ and the aerodynamic surface roughness length $z_o$ are calculated from measure wind speed profiles. By projecting the straight line of the measured profile in the right graph of Figure 2 (using the W-direction wind profile) to the zero speed axis we find the value for the roughness length to be $z_o \approx 0.01$, which is consistent with $z_o$ for fairly level grass plains. The roughness length is independent of wind speed. The normalised friction velocity $u_*/\bar{u}_h$ depends on the height *h* at which we wish to project the wind speed. For example, at 3 m a.g.l., $u_*/\bar{u}_{3m} = 0.07$. Using Table 1 below we can derive speeds at heights above the measured value, as long as the surface roughness is consistent with the above. This should be typical of alpine surface of Yukon mountain tops and where the station is on relatively large flat ground.

| Height | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 15 | 20 | 23 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 40 | $u_*/U_{40}=$ | 0.048 | 1.80 | 1.57 | 1.45 | 1.38 | 1.33 | 1.30 | 1.27 | 1.24 | 1.22 | 1.20 | 1.13 | 1.09 | 1.07 | 1.04 |
| 30 | $u_*/U_{30}=$ | 0.050 | 1.74 | 1.51 | 1.40 | 1.34 | 1.29 | 1.25 | 1.22 | 1.20 | 1.18 | 1.16 | 1.09 | 1.05 | 1.03 | 1.00 |
| 23 | $u_*/U_{23}=$ | 0.052 | 1.68 | 1.46 | 1.36 | 1.29 | 1.25 | 1.21 | 1.18 | 1.16 | 1.14 | 1.12 | 1.06 | 1.02 | 1.00 | |
| 20 | $u_*/U_{20}=$ | 0.053 | 1.65 | 1.43 | 1.33 | 1.27 | 1.22 | 1.19 | 1.16 | 1.14 | 1.12 | 1.10 | 1.04 | 1.00 | | |
| 15 | $u_*/U_{15}=$ | 0.055 | 1.59 | 1.38 | 1.28 | 1.22 | 1.18 | 1.14 | 1.12 | 1.09 | 1.08 | 1.06 | 1.00 | | | |
| 10 | $u_*/U_{10}=$ | 0.058 | 1.50 | 1.30 | 1.21 | 1.15 | 1.11 | 1.08 | 1.05 | 1.03 | 1.02 | 1.00 | | | | |
| 9 | $u_*/U_9=$ | 0.059 | 1.48 | 1.28 | 1.19 | 1.14 | 1.09 | 1.06 | 1.04 | 1.02 | 1.00 | | | | | |
| 8 | $u_*/U_8=$ | 0.060 | 1.45 | 1.26 | 1.17 | 1.12 | 1.08 | 1.04 | 1.02 | 1.00 | | | | | | |
| 7 | $u_*/U_7=$ | 0.061 | 1.42 | 1.24 | 1.15 | 1.09 | 1.05 | 1.02 | 1.00 | | | | | | | |
| 6 | $u_*/U_6=$ | 0.063 | 1.39 | 1.21 | 1.12 | 1.07 | 1.03 | 1.00 | | | | | | | | |
| 5 | $u_*/U_5=$ | 0.064 | 1.35 | 1.17 | 1.09 | 1.04 | 1.00 | | | | zo | 0.01 | | | | |
| 4 | $u_*/U_4=$ | 0.067 | 1.30 | 1.13 | 1.05 | 1.00 | | | | | k | 0.4 | | | | |
| 3 | $u_*/U_3=$ | 0.070 | 1.24 | 1.08 | 1.00 | | | | | | | | | | | |
| 2 | $u_*/U_2=$ | 0.075 | 1.15 | 1.00 | | | | | | | | | | | | |
| 1 | $u_*/U_1=$ | 0.087 | 1.00 | | | | | | | | | | | | | |

**Table 1 - This table offers a guideline for projecting wind speed increase from a measured point to a higher level a.g.l. It is based on the typical surface roughness length on mountain tops and assumes a large flat terrain upwind.**

Referring to Figure 3 the logarithmic profile of Equations (1) and (2) are compared to the W-direction wind flow. Equation (2) shows good match below 5 m and slight overestimates above. Equation (1) as stated earlier a good match above 5 m.

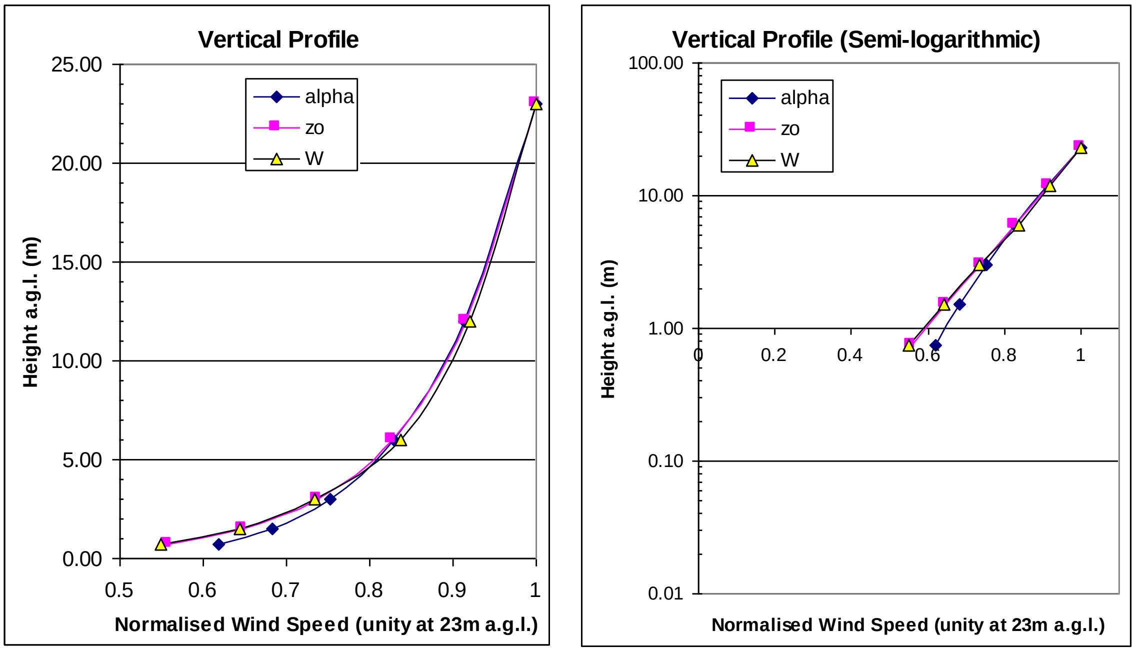


**Figure 3 - Two analytical profiles measured against a measured profile on a relatively flat terrain (W-direction). Alpha is the power law equation and zo is the logarithmic equation. Note that on the semi-log scale (right graph) the zo line is very straight, as is the measured profile.**

As Figure 4 on the next page shows, the analytical profiles work reasonably well for flat terrain, but not where upwind slope rising immediately before the tower.

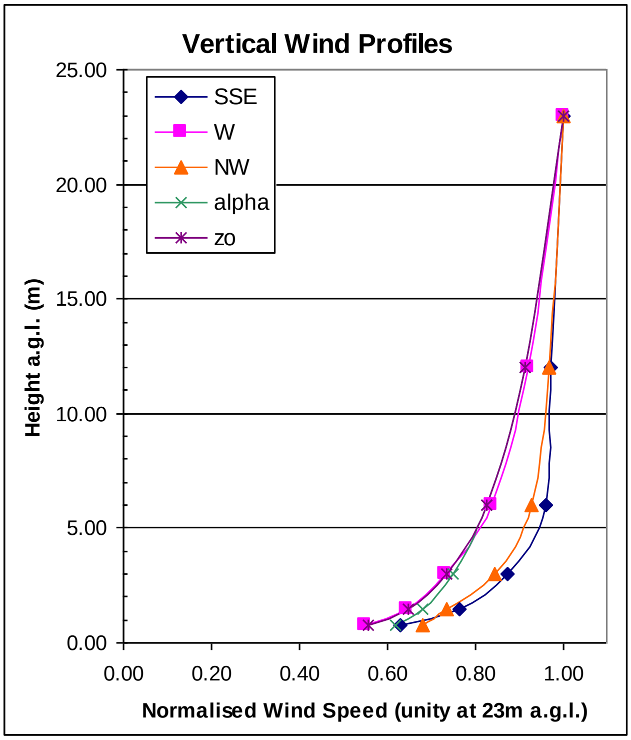


**Figure 4 - Compares the analytical profiles to measured profiles for the W-direction, which is flat terrain, and the SSE, NW directions which are more representative of hill top flows.**

## A Quick-Fix to Calculating Projections in Speed-up Areas

If we observe the profile data for the SSE direction (see Figure 4) we find that the increase in speed from 6 m to 23 m a.g.l. is approximately 1.03. From 3 m to 23 m it is approximately 1.16. Table 2 below gives estimates to help project wind speed from a measured level to a higher level.

Hill Speed-Up

| Height | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 15 | 20 | 23 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 40 | 1.50 | 1.29 | 1.19 | 1.13 | 1.09 | 1.06 | 1.05 | 1.05 | 1.05 | 1.05 | 1.04 | 1.03 | 1.03 | 1.02 |
| 30 | 1.47 | 1.27 | 1.17 | 1.11 | 1.07 | 1.04 | 1.04 | 1.04 | 1.03 | 1.03 | 1.02 | 1.02 | 1.01 | 1.00 |
| 23 | 1.46 | 1.26 | 1.16 | 1.10 | 1.06 | 1.03 | 1.03 | 1.02 | 1.02 | 1.02 | 1.01 | 1.00 | 1.00 | |
| 20 | 1.45 | 1.25 | 1.16 | 1.10 | 1.05 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.01 | 1.00 | | |
| 15 | 1.44 | 1.24 | 1.15 | 1.09 | 1.05 | 1.02 | 1.01 | 1.01 | 1.01 | 1.01 | 1.00 | | | |
| 10 | 1.43 | 1.23 | 1.14 | 1.08 | 1.04 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | | | | |
| 9 | 1.43 | 1.23 | 1.13 | 1.08 | 1.04 | 1.01 | 1.00 | 1.00 | 1.00 | | | | | |
| 8 | 1.42 | 1.22 | 1.13 | 1.08 | 1.03 | 1.00 | 1.00 | 1.00 | | | | | | |
| 7 | 1.42 | 1.22 | 1.13 | 1.07 | 1.03 | 1.00 | 1.00 | | | | | | | |
| 6 | 1.42 | 1.22 | 1.13 | 1.07 | 1.03 | 1.00 | | | | | | | | |
| 6 | 1.42 | 1.22 | 1.13 | 1.07 | 1.03 | | | | | | | | | |
| 5 | 1.38 | 1.18 | 1.09 | 1.04 | 1.00 | | | | | | | | | |
| 4 | 1.32 | 1.14 | 1.05 | 1.00 | | | | | | | | | | |
| 3 | 1.26 | 1.08 | 1.00 | | | | | | | | | | | |
| 2 | 1.16 | 1.00 | | | | | | | | | | | | |
| 1 | 1.00 | | | | | | | | | | | | | |

**Table 2 – Estimated multipliers for projecting wind speed from a measured point to a higher level. It is based the measured profile on Sumanik with the station close to the slope and the wind coming perpendicular to the ridge.**

## Conclusions and Recommendations

Tables 1 and 2 offer some guidelines for making projections. These are based solely on the data studied at Mount Sumanik during July 1999. More work would be required to ensure that this information is reasonable.

Such work that needs attention are: revisiting the vertical profile for wind speed for Haeckel Hill, taken during the early 1990's, studying the turbulence intensity in these profiles, comparing the relationship between the speed and profile shape, and comparing the profile shape, speed and the shape of the hill (Sumanik and Haeckel Hill).