Investigating wind characteristics across Mount Washington

1.0 Introduction

Mount Washington has observed some of the fastest recorded wind speeds on earth, with the fastest gust ever recorded by man being 231 miles per hour on April 12th 1934 (MWO, 2017). With these phenomenal records, it brings into interest the reasons for such speeds and the resultant effects for the summit and the rest of the MW valley system. To generalise, the mountain environment plays an important role in the earth system, these high altitude areas, show rapid change in a spatially small area, and often are characterised by sensitive process that can abruptly differ with climate (Beniston, 1994, p.22). Beniston (1994).

Wind is an often underrepresented climatic factor (Goldman, 2014), however it does form an important synergy with three other factors, topography, snow and vegetation. Both wind and topography have a mechanical relationship whereby, variations in topography directly affect wind direction and speed. This resultant wind forcing can cause snow redistribution and ablation, while also causing vegetation stress. Lastly the relationship between snow variation and its insulating effect upon vegetation is another dimension of change.

2.0 Study area

Mount Washington is located in the north-east U.S.A. It is part of the Appalachian trail and the Presidential and White mountain ranges.

3.0 Project Theory

This project aims to evaluate the effect of topography upon prevailing wind over the summit and valley of MW, over a 45-minute study.

3.1 Specific objectives

- To represent data in a spatial form enabling summit specific analysis using wind ratio and deflection
- To represent data in a spatial form enabling valley wide analysis using wind ratio and deflection
- Undertake statistical analysis of both T tests and Variance for summit and valley points
- Infer possible application of further study from wind recordings across MW.

4.0 Methodology

4.1 Stations

The nelson crag transect recorded from 29/10/2016 to 03/11/16 at Pinkham Notch, the main valley site at the lowest elevation of 627m. While also recording the same data at Lowes Bald Spot. However, this point was not actually erected at Lowes Bald Spot due terrain preventing passage to the point, we feel data recorded was hampered by sheltering from trees and therefore excluded this data from the study. Tuckerman transect was erected from 30/10/2016 to 02/11/216 and consisted of the Tuckerman ravine wind stations, distributed across the centre (1341m) of the basin and the north (1363m) and south (1369m) face of the ravine. Again terrain influence point placement. Control data was also provided for the Hermit Lake Hut at 1181m.

4.2 Summit recordings

The summit experiment consisted of a peak wide distribution of students recording wind speeds 12 times within a minute for 10 points within 45 minutes, transects were distributed in an azimuthal direction (N, NE, E, SE, S, SW, W, NW) from the summit. As well as wind speed, a single wind direction reading and GPS position for each point was recorded. There was approximately 5 seconds between each reading for a point, and 5 minutes between each point for a transect. This provided 80 points of summit wind conditions. Timings between each reading within a point was marked by a whistle blown from the central observatory parapet. Figure 1 shows data points.

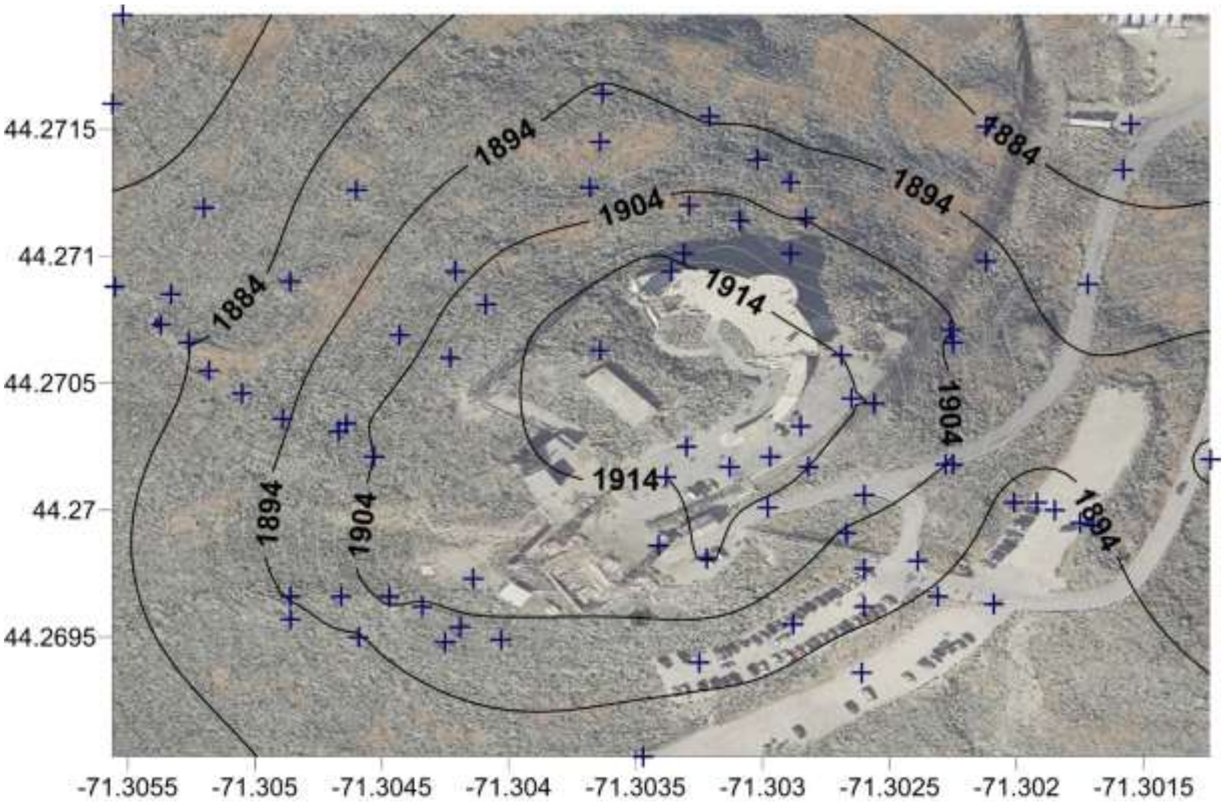


Figure 1: Diagram showing distribution of summit points, overlaid upon a satellite image of the summit observatory. Satellite imagery from DigitalGlobe (2017).

Data for the summit parapet has also been provided by the MWO (2016), which gives a control and comparison for wind speeds and directions across our stay and across the summit experiment time.

5.0 Results

5.1 Wind

Figure 2 below represents the average wind speeds and wind direction recorded at each point upon the summit. As well as this the average wind speeds and direction throughout the valley encompassing Tuckerman ravine, Hermit lake hut and Pinkham notch.

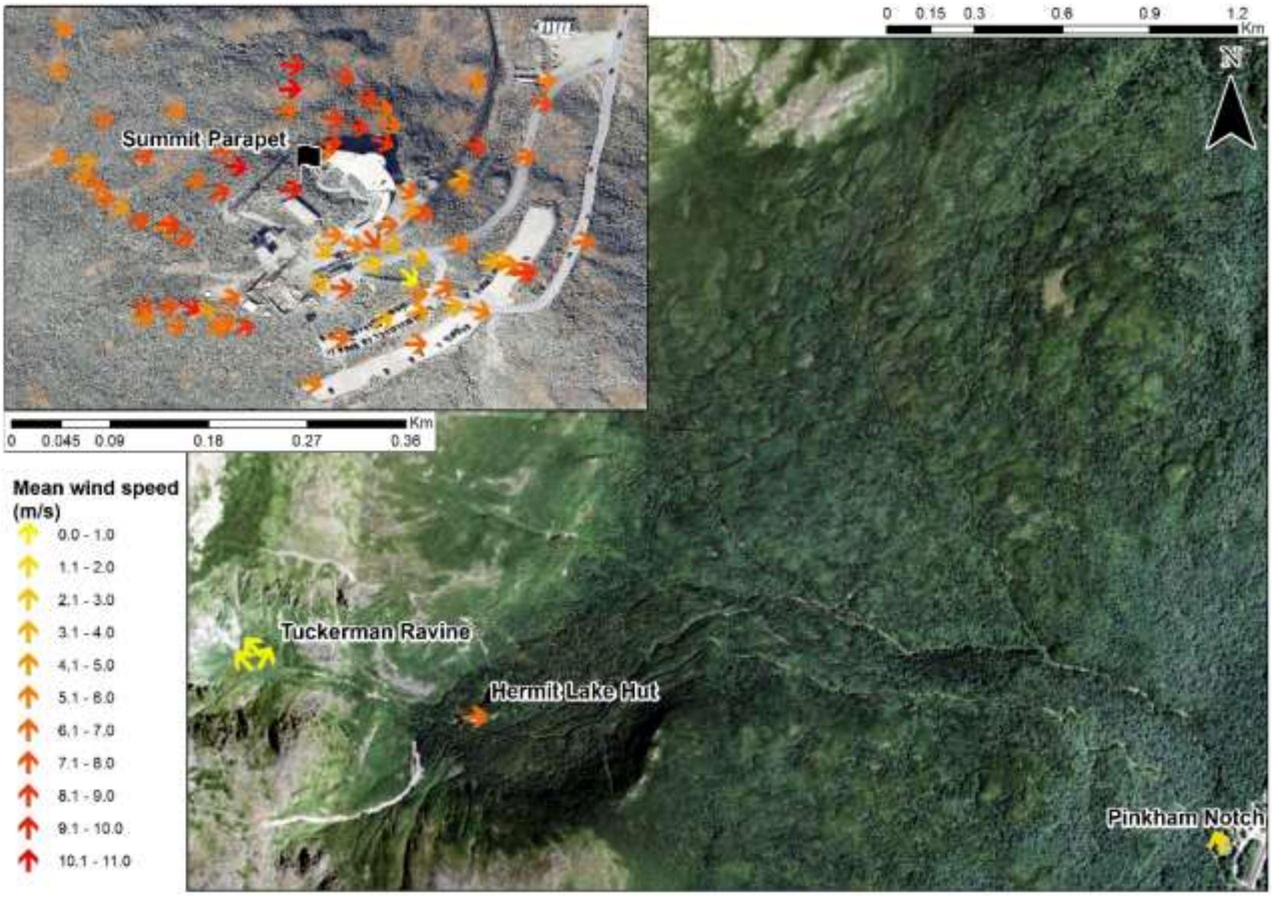


Figure 2: The map above shows average wind speed and point direction across the whole study area, over the period of the 45-minute experiment. While the data at the summit was manually collected, the rest of the data is pre-installed weather stations by both the University of Portsmouth research party and the MWO. Satellite imagery from DigitalGlobe (2017).

It is next necessary, to break the focus down into the summit in isolation and then the rest of the valley.

5.1.1 The isolated summit

The mean wind speed at MW summit has a max speed of 10.33 metres per second. The speed across the majority of the summit is 6 to 7 metres per second. The max speeds can be seen on the isotach

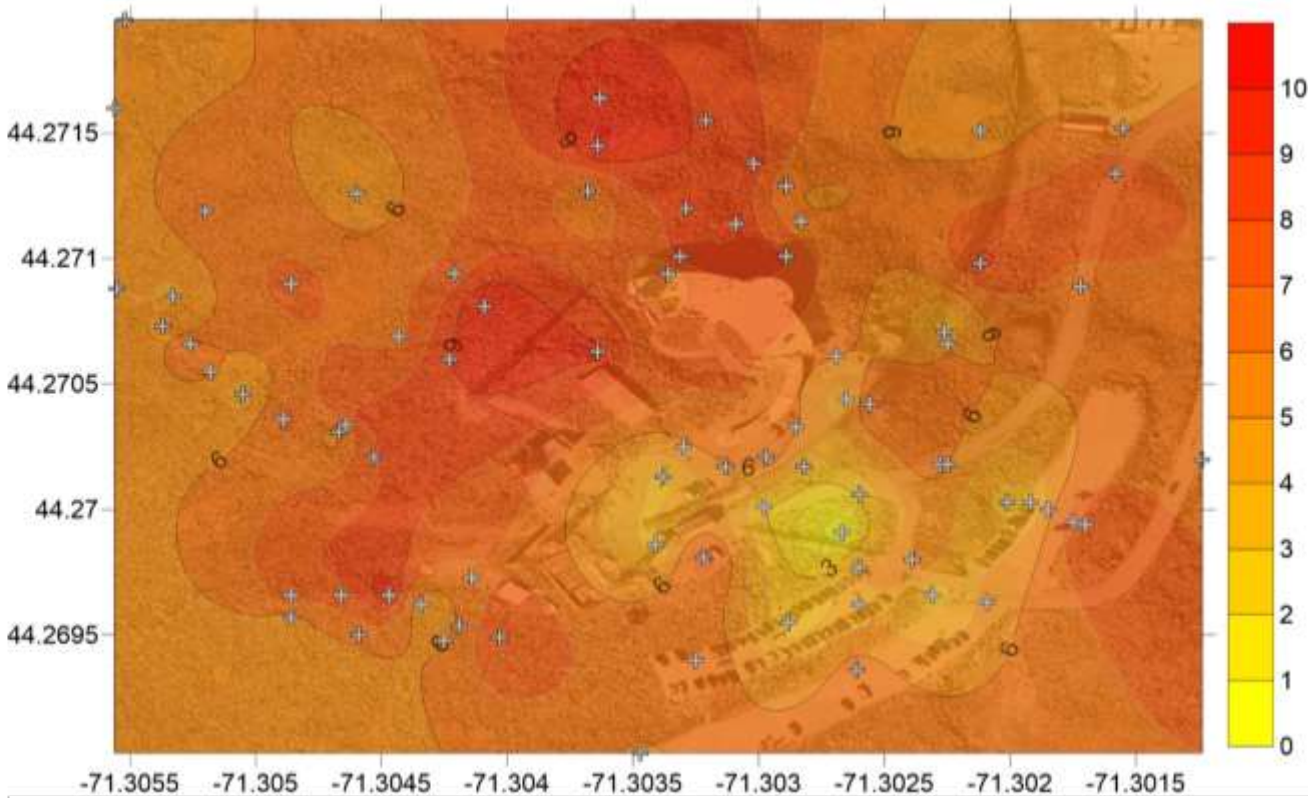


Figure 3: The isotach diagram above represents average wind speeds recorded at the summit over the 45-minute experiment, 80 points where recorded giving a range of wind speeds as represented by the scale, with a maximum of 10.33 ms^{-1} and a minimum of 0.08 ms^{-1}. Satellite imagery from DigitalGlobe (2017). The scale goes from yellow to red, minimum to maximum accordingly.

diagram above where the darker red areas show a speed above 8 metres per second, and the brighter yellow areas show minimums which concentrate towards the south east of the summit complex. Generally, speeds seem to adhere to the expected average the further the distance away from the summit complex with less maximums and minimums. Figure 4 is a diagram for prevailing wind as recorded at the summit parapet. It shows a west south westerly wind and a wind speed of between 10.80 ms^{-1} and 10.90 ms^{-1} for 50% of the period of the 45-minute experiment. There's also a max speed of 13.10 ms^{-1} for 10%.

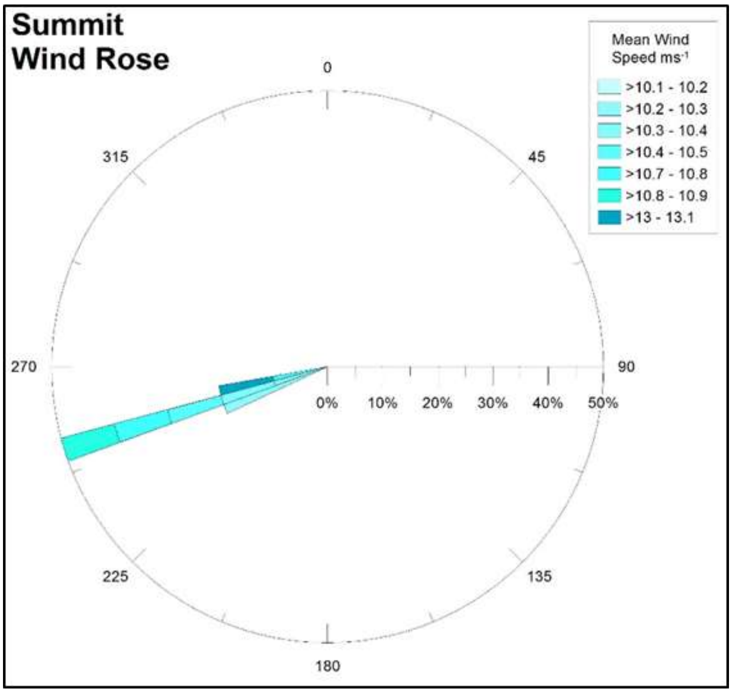


Figure 4: A wind rose showing the direction and speed of the prevailing wind as recorded from the summit parapet control point. Data from MWO (2016).

5.1.1.1 Wind Ratio

In figure 5 and 6, data for wind ratio is shown, comparing the exact point where wind at the parapet and wind on the ground was both very similar and very dissimilar. The range of ratio is from 0.0079 to 0.9870, with one point in particular showing a low ratio which is that to the south south east of the observatory above the first carpark. Points show approximately 60% affinity to the summit.

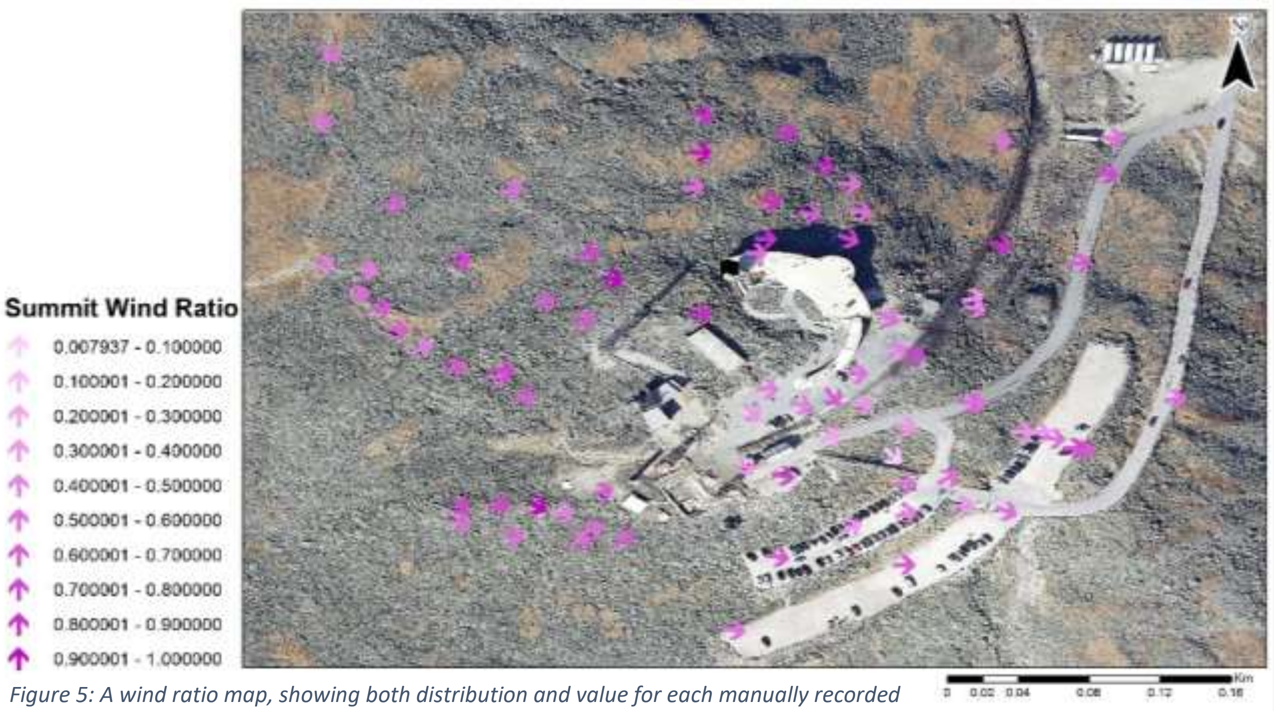


Figure 5: A wind ratio map, showing both distribution and value for each manually recorded ground point, in comparison to the prevailing wind showing in figure 4. Satellite imagery from DigitalGlobe (2017).

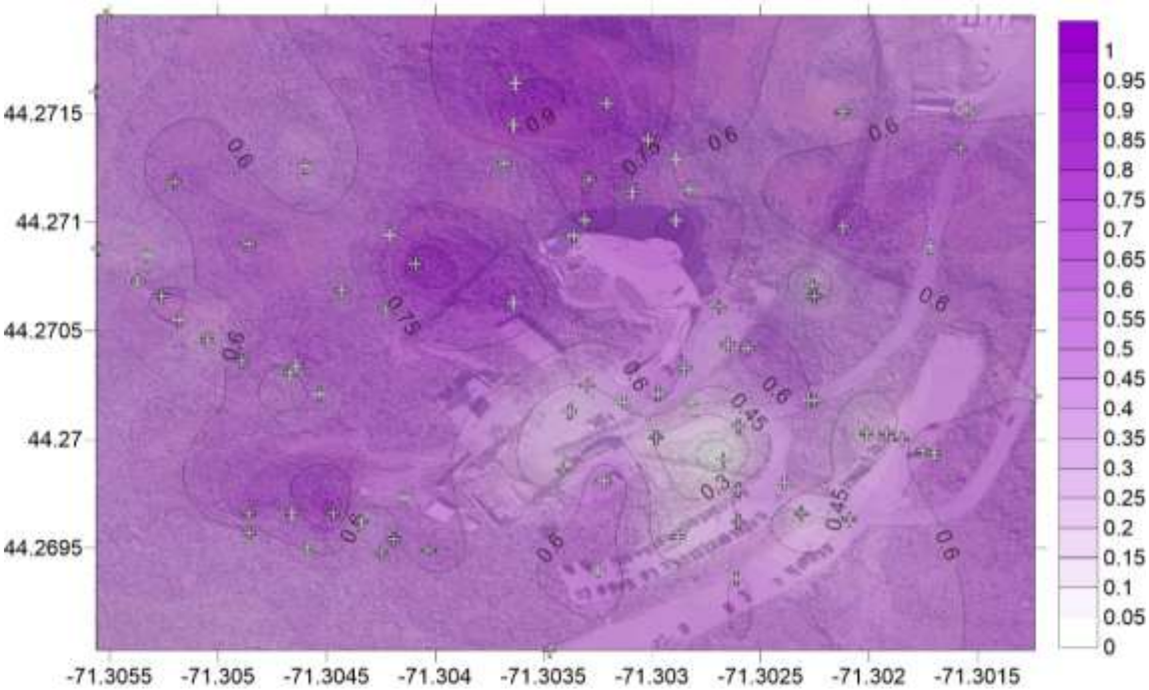


Figure 6: A wind ratio isotach diagram showing the trend of wind ratio to the summit across the observatory complex. Satellite imagery from DigitalGlobe (2017).

5.1.1.2 Wind Deflection

As is represented in figure 7 the north and north east and north west area of summit show moderate veering in orange, which is a rotation clockwise at the point compared to the west south westerly direction in figure 4. The backing is the opposite to this and is shown in blue. While 0° ± 5° of change is represented in black, as little to no deviation from the parapet. This backing and veering relationship is in line with Oke (1987, p.187) wind flow from smooth to rough surface study.

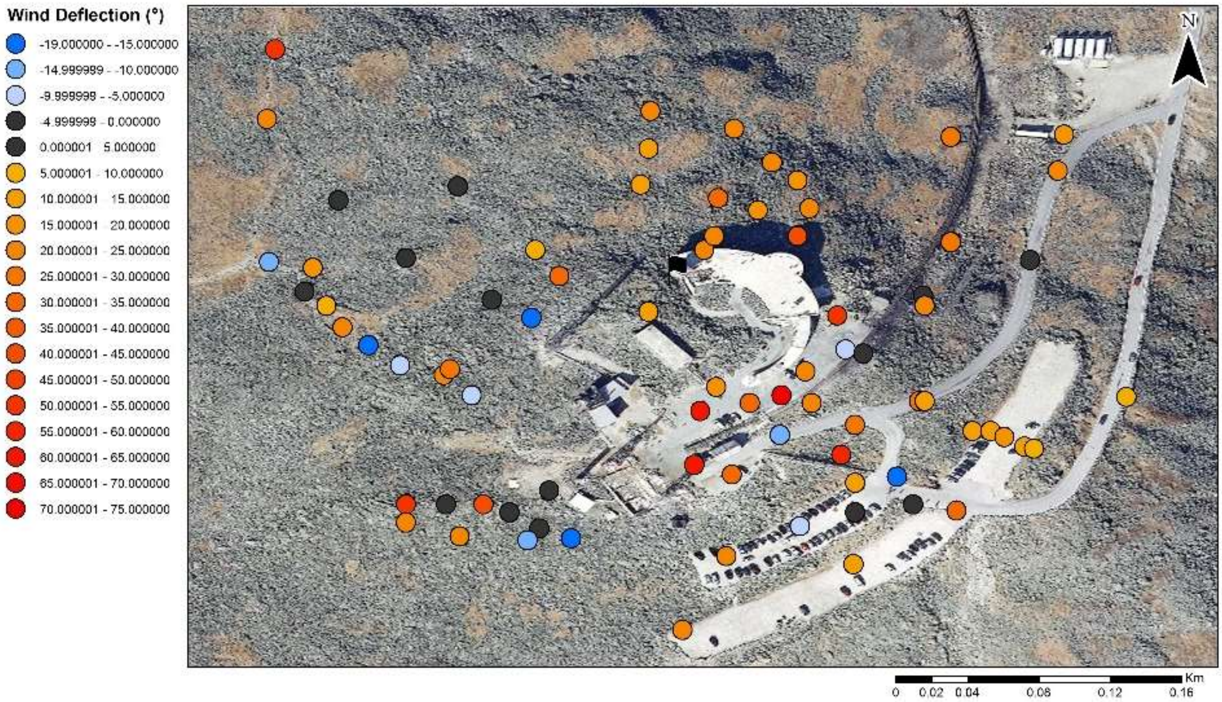
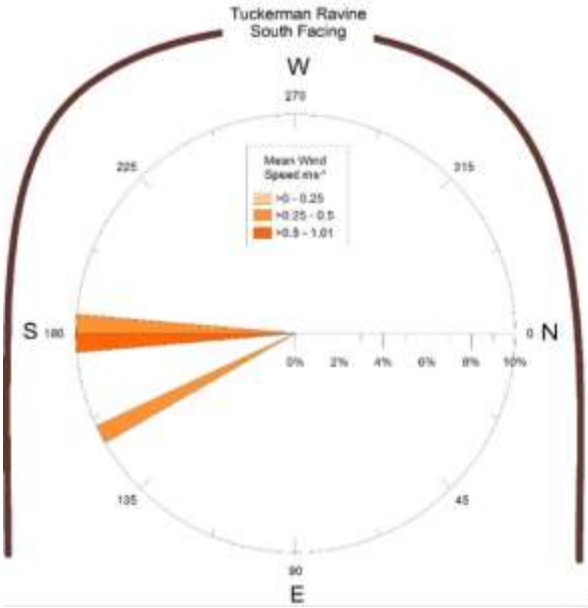


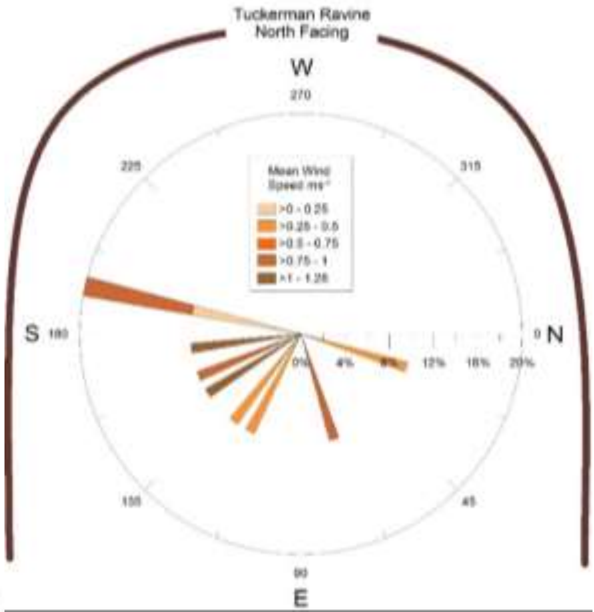
Figure 7: Wind deflection map, showing both backing and veering of the wind at each manual ground point in comparison to the summit parapet direction across the experiment. Satellite imagery from DigitalGlobe (2017).

The veering is small but still seen in areas of the summit such as those in the south east and south west. Both veering and backing reach a maximum of 72° and -19° respectively.

5.1.2 Wind throughout the valley

The MW valley mean wind speed and direction results can be characterised from figure 2. There is a large variation for both direction and speed, this is also in parallel with the large spatial variation. Tuckerman Ravine slope points record direction of north west (320°), the basin point shows a variation of 70 degrees to north east (29.2°). Tuckerman points have weak average speed of under $1ms^{-1}$. Hermit Lake shows a similar reading to that of the summit recordings with a westerly direction of 84° and an average speed of 6.19ms^{-1}. Pinkham notch shows a direction of 322°, different from the summit by 93°, however it is parallel the valley. Pinkham average speed was weak at 1.06ms^{-1}.





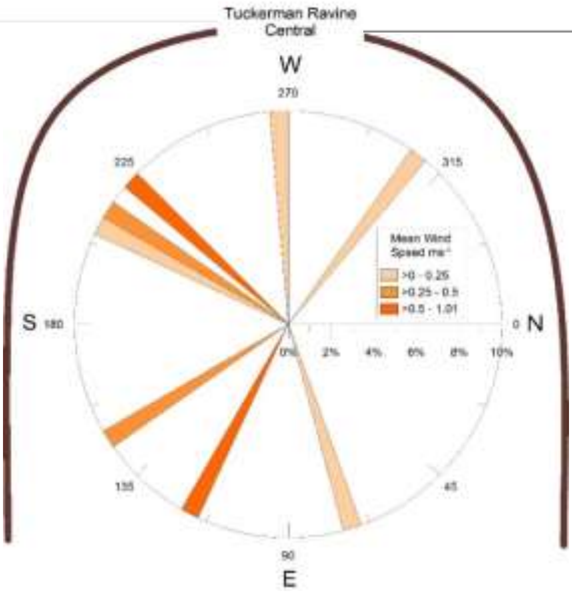
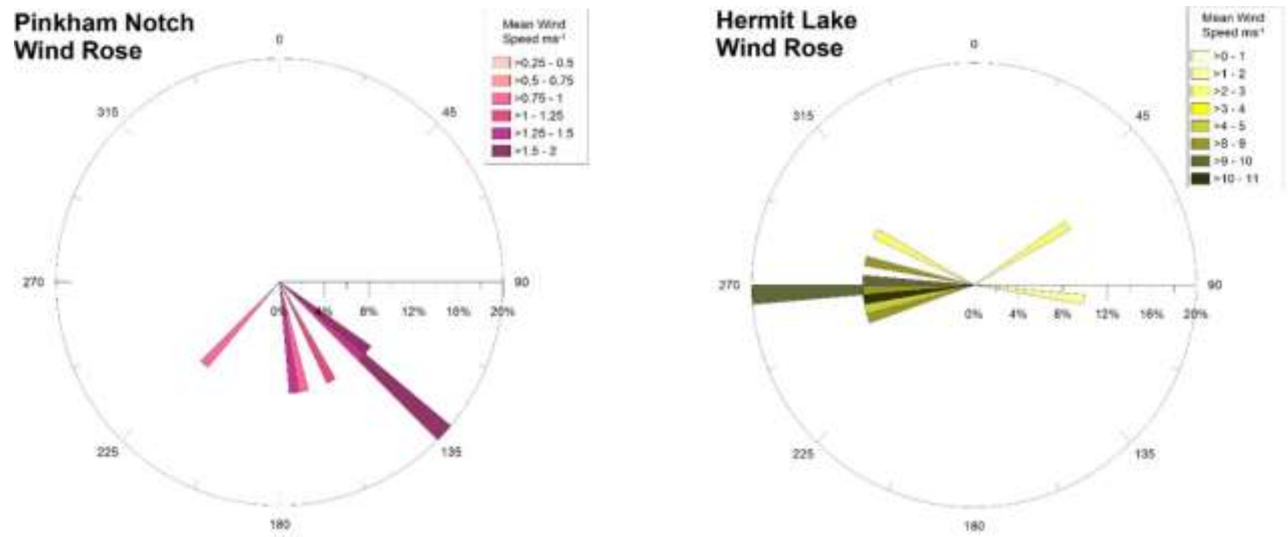


Figure 8: To right and above are wind roses showing the wind data across the 45-minute experiment at all Tuckerman ravine stations. They are oriented to the direction of orientation of the ravine within the valley.

Figure 9: Below are wind roses showing wind data across the 45-minute experiment at both Hermit lake and Pinkham notch.



5.1.2.1 Wind Ratio

Wind ratio throughout the valley never reaches more than that of 0.576 or 57.6% of the summit parapet. Figure 10 below shows ratio of Tuckerman ravine moving from 2% to 6% from the south facing site to the north facing site accordingly. While hermit lake is that of the closest ratio, Pinkham notch is 10% of average wind speed compared to that at the summit.

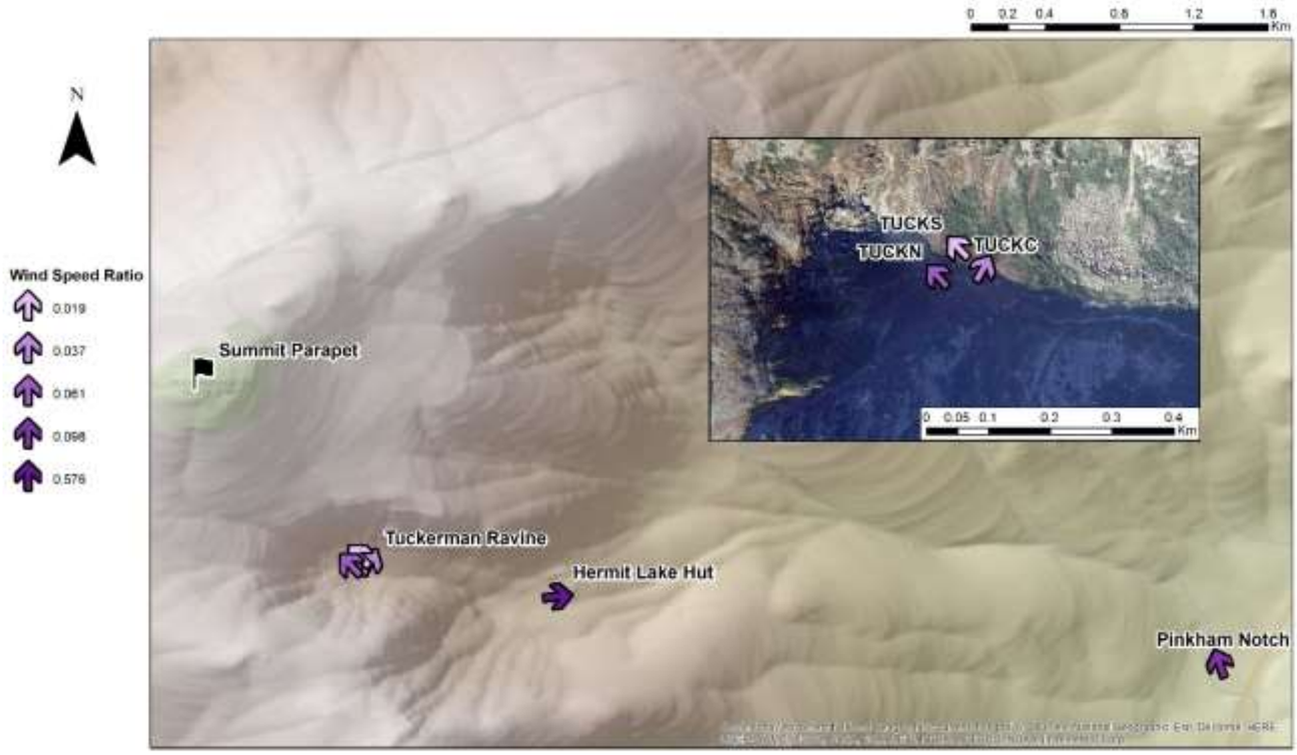


Figure 10: Map showing the wind ratio across the valley stations, in comparison to the summit parapet. Satellite imagery from DigitalGlobe (2017).

5.1.2.2 Wind Deflection

The valley wind deflection is shown in figure 11 below. The map shows a trend of backing across the valley with the largest amount of deflection at the Tuckerman ravine slope sites both North and south were deflected by -117.4° and -118.5° respectively, while the basin was deflected by -93.6°. Deflection is also seen at Pinkham notch station -45.8°.

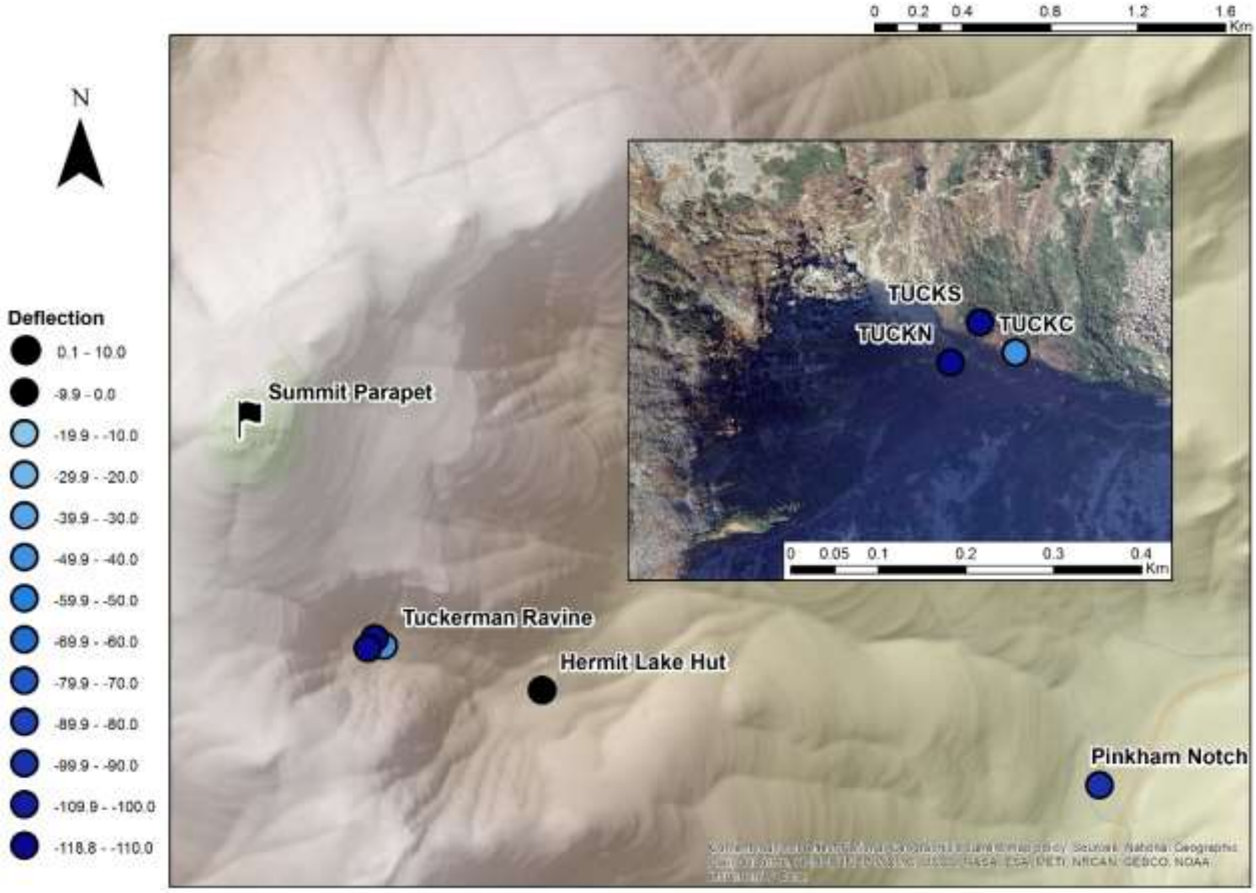


Figure 11: Map showing wind deflection across the valley stations, this is the deflection from the prevailing wind recorded at the parapet. Satellite imagery from DigitalGlobe (2017).

Hermit lake, as is shown in figure 10 shows very little deviation from the parapet at only 9°.

6.0 Discussion

6.1 Reasons for characteristics of summit wind

6.1.1 Global wind controls

Firstly, it is important to look at the synoptic condition for 1st November 2016, this is represented below in figure 12. The figure shows a high pressure system over the MW area, as a result calm conditions ensued (McIlveen, 1992). The air mass was continental from the west, causing drier air. The synoptic conditions influence speeds for the study, the yearly average for wind speed on the summit is $14.30ms^{-1}$ (MW Avalanche Center, 2017), however average recorded wind speed at the parapet for the experiment was 75% of the yearly average at $10.75ms^{-1}$. This relationship was recognised by McIlveen (1992, p.392) “wet and windy weather is associated with low pressure”.

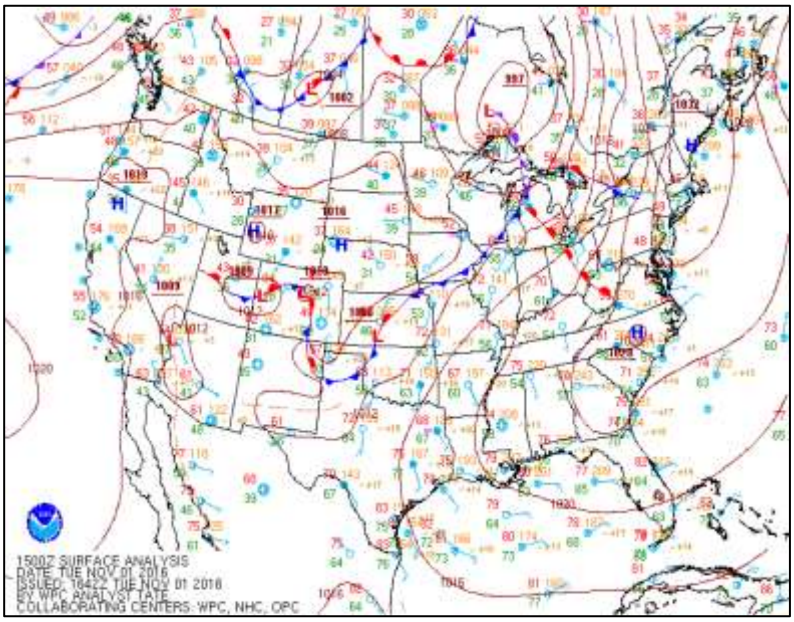


Figure 12: Synoptic weather conditions for 01/11/2016, provided by NOAA (2016).

A secondary global control is the jet stream upon wind forcing at the summit. Siedel et al (2009) writes “for 50% of days in the year MW spends its time within the free atmosphere”. Free atmosphere is above the boundary layer, where both the of earth surface friction on the air motion is insignificant (American Metrological Society, 2012) as a result summit wind and climate are influenced largely by free atmosphere factors, namely the North Atlantic Jet Stream and Rossby waves. To the north east of New Hampshire over the North Atlantic is the North Atlantic jet stream maximum (Hoskins and

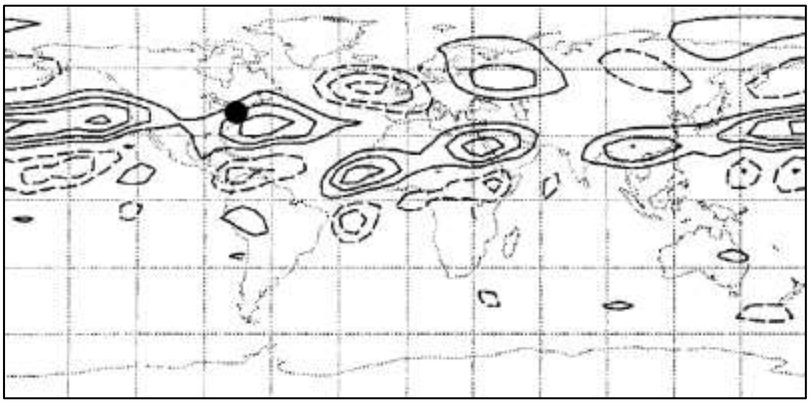


Figure 13: A model representing the placement of the north atlantic jet stream maximum. Retrieved from Hoskins and Ambrizzi (1993). The location of this is north east from MW as shown by the black dot.

Ambrizzi, 1993) as shown in figure 13. This maximum leaves MW directly in the Jet Streak, which is the upward gradient from a trough to a peak in the jet, in figure 14 the red area shows this intense streak. This jet streak gives rise to high winds within the jet that can result in speeds of up to 82.31ms^{-1} (Weather World 2010: University of Illinois, 1999) while the jet stream is constantly moving above and below the latitude of MW, surrounding Rossby waves often have similar high winds and therefore similarly influence the free atmosphere at the summit. While global factors often hold importance within climatic control, it is important to also recognise the local influence of the specific case study.

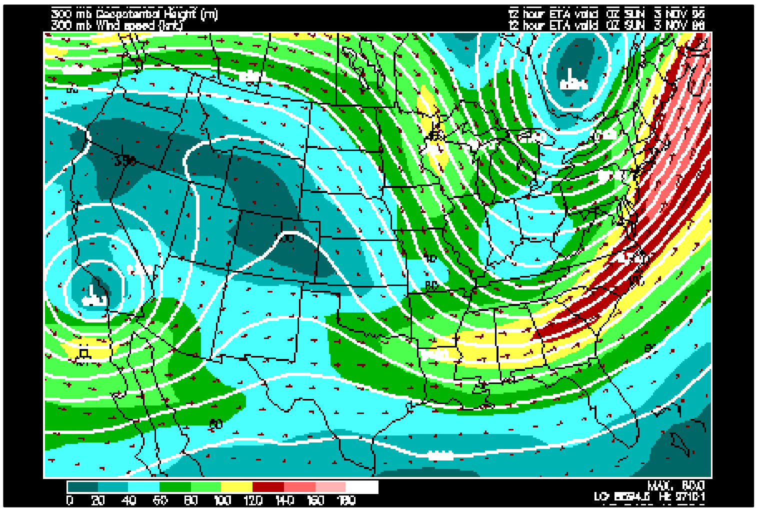


Figure 14: Weather chart showing jet streak over the New Hampshire state, with the colour representing wind speed. Retrieved from Weather World 2010: University of Illinois (1999).

6.1.2 Local wind controls – Isolated Summit

The topography of the presidential range is a large ridge formation. The result of this ridge is a steep wind barrier. An effect upon wind masses flowing over this topography is the Bernoulli effect. This is the process of wind traveling up the mountain face, increasing velocity, reaching the summit and resulting in strong downslope leeward winds (Sun and Sun, 2015). Acceleration is due to the mountains compression effect (Barry, 2013; Oke, 1987, p.182); the summits relationship with the troposphere boundary layer, a consistent layer among global topography variation. Mountains therefore form a 'pinch point' as mentioned above. Local ground features form a vital role in summit and leeward wind forcing. Initially this accelerating wind jet meets a dome summit, allowing reduced obstruction over the mountain, this is a positive erosion feedback. Dome summit aspect and manual wind speeds can be seen below in figure 15. This terrain analysis and T testing showed, that manual

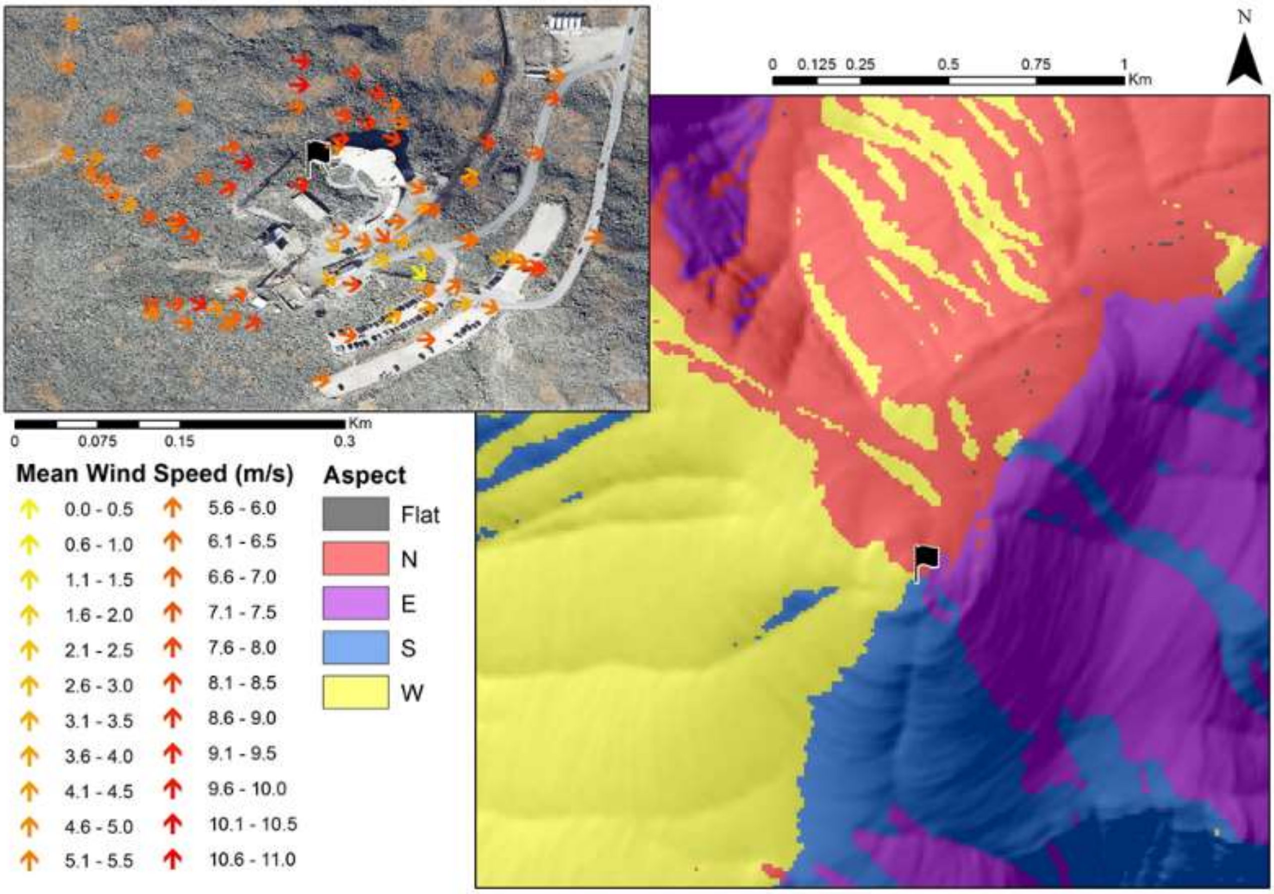


Figure 15: Map showing distribution of manual summit points and mountain aspect.

wind speed data is significantly different to parapet speeds, P value of 0. However, when assessing aspect an ANOVA test again showed a statistically significant difference, P value of 0.016. Therefore, the speed of the wind is effected by point aspect.

Aspect	North	East	South	West
North	-	0.009	0.043	0.481
East	0.009	-	0.319	0.029
South	0.043	0.319	-	0.141
West	0.481	0.029	0.141	-

Table 1: Table showing the results of 6 T tests and the resultant P values, of which 3 show a significant statistical difference between aspect and average wind speed. Produced by Singleton (2017).

The table above provides P values for wind speed differences according to aspect. There is increased frictional bending of wind in a left hand direction, as airflow meets an area of roughness such as the mountain summit. Not only is this free air slowed and backed in a leftward direction, upon exiting down towards the valley or off over the summit, there will be a final leftward tendency in the northern hemisphere (Oke, 1987, p.188), such is the case for MW Summit; best illustrated in figure 16. The significant values in table 1 do relate to the trends outlined by Oke (1987, p.188).

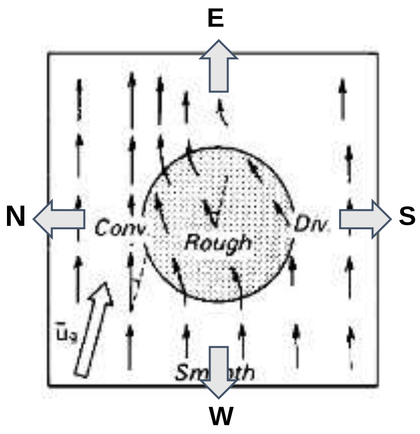


Figure 16: Diagram or frictional effect in the northern hemisphere (Oke, 1987, p.188).

The lee of the mountain for the wind direction of the day is east south east which lies between these two significant differences. Showing both topographic and artificial influence. The degree of artificial influence from buildings is difficult to quantify without air flow modelling, however basic deflection is attainable from figure 7, and exemplified by points to the south east of the observatory such as F8.

Aspect	P Value	Reasoning
North-East	0.009	Different because the east is in the lee of mountain and observatory
North-South	0.043	Different because the south is in the lee of mountain.
East-West	0.029	Different because the east is in the lee of the observatory.

Table 2: Representing significant aspects and possible reasons for average wind speed differences.

6.1.3 Local wind controls – Valley

Comparison between valley sites and the summit parapet is necessary as shown in figures 10 and 11. The statistical tests for wind speed and direction are shown in table 3 below.

Statistical Test	Property	Variable	Means	Elevation	P-Value
ANOVA	Speed	Parapet	10.75	1917m +	0
		Tuck C	0.402	1341m	
		Hermit Lake	6.19	1181m	
		Pinkham	1.05	627m	
ANOVA	Direction	Parapet	265	1917m +	0.002
		Tuck C	200.8	1341m	
		Hermit Lake	231.9	1181m	
		Pinkham	162.44	627m	

Table 2: Results of statistical analysis upon valley sites and summit parapet. Produced by Singleton (2017).

Table 3 ANOVA P values show a significant degree of difference between all sites, which infers ground influence upon prevailing wind speeds and direction. It could be assumed that simply wind speed and direction would diverge with elevation, Hermit Lake elevated recordings do follow this relationship, arguably, when means between here and the parapet are compared. However, when considering Tuckerman Ravine relationships are not so simple. As is shown in figure 2 and 10, values are wildly different from the parapet. This is due to westerly winds deflecting sensors in basin, over other wind directions. Eddying within such an elevation step is outlined by Oke (1987), this is caused because of flow separation from a prevailing wind that cannot adjust itself to the depression of the ravine. As a result, wind both flows over and into the basin but often forms eddy's (Oke, 1987), this would account for the differing wind direction, speeds are lowered due to the coupling of topographic interference and the synoptic high pressure system which reduced initial wind speed. Such effects are described as Mechanical. Thermal effects may also be operating within this topographic feature, however point elevation makes evidence of this impossible. It would be expected that wind direction would be up slope during day (anabatic), down slope at night (katabatic). Arguably the snow in the basin would reduce thermal effect in day but increase cooling at night causing katabatic drainage. However, this is theoretical (Poulos and Zhong, 2008). At Pinkham Notch valley wind funnelling is present with lowest wind speeds over the longest distance from the summit, and a wind direction in parallel with the valley.

6.2 Application of wind measuring:

Mount Washington 'windy' dynamics are widely used for popular product testing. Often products from industries such as aviation (Henson and Anatta, 1999), military and aerospace have been sited at the extreme summit. Consumer products commonly feature in summit testing with examples such as mountain wear from eastern mountain sports, a clothing provider for the observatory team (Mountwashington.org). Damage to buildings and the application of aerodynamic building as shown in a study by Cermak (1976). Wind loading can cause damage to structures and the effect of force and flow upon buildings is crucial to understand mitigation towards wind proof buildings.

Climatically, wind is a controlling factor on snow distribution (Marks & Winstral, 2001) and vegetation (Kullman, 2010) stress. Hiemstra et al (2002) evaluates the relationship between wind and snow distribution, findings show that snow distribution and vegetation are not separate, and often increased vegetation (both macro and micro) effects wind flow dynamics as well as topography. Further study across the valley could derive interesting results on further wind dynamics and there control on winter snow, albedo feedback, vegetation distribution, mountain treeline and overall mountain climate.

Critical Reflection

Both the summit and the valley stations yielded various obstacles. During the summit experiment more people and time would give a more comprehensive wind survey of conditions. Likewise, the ability to record at the summit antennas would increase data coverage, however the rime ice accumulation was a dangerous hazard. Valley points, namely Tuckerman Ravine, and Lowes Bald Spot, would have been generated better results at higher elevations. Giving a better representation a ravine microclimate and a serviceable dataset for Lowes Bald Spot.

7.0 Conclusion

To summarise this mountain summit study has represented the real effect of local factors upon the initial free air wind speed and direction. Within a sharply inclining summit setting wind speed is accelerated and direction is conserved due to the compressional boundary layer and the resultant Bernoulli effect. However, on the leeside of the mountain, differing landforms result in differing wind patterns. The interplay between mechanical forcing and thermal forcing can cause an array of resultant wind speeds and directions as shown in Tuckerman Ravine specifically, where often speeds were as little as 2% that of the summit parapet and deflection was at -118.5°. Importantly, synoptic conditions have an overriding control upon the scale of wind characteristics, and can supersede topographic forcing. Nevertheless, topographic themes both west of the summit and east of the summit are differing and the effect of topography is significant and will vary with the scale of topographic feature and representability of the data point. What is clear from this study is that both ravine and valley features, can dramatically effect the prevailing wind direction received at the summit, but often global climate is an overriding influence upon speed.

8.0 Bibliography

MWO (2017). Mountwashington.org. Retrieved 9 February 2017, from https://www.mountwashington.org/about-us/history/world-record-wind.aspx

Beniston, M. (1994). Mountain environments in changing climates (1st ed.). London: Routledge.

Goldman, J. (2014). The Forgotten Part of Climate Change: Slower Winds. University Of Washington: Conservation This Week. Retrieved from http://www.conservationmagazine.org/2014/09/the-forgotten-part-of-climate-change-slower-winds/

Weather – MW Avalanche Center. (2017). Mountwashingtonavalanchecenter.org. Retrieved 19 February 2017, from http://www.mountwashingtonavalanchecenter.org/information/weather/

McIlveen, J. (2010). Fundamentals of weather and climate (1st ed.). Oxford: Oxford University Press.

NOAA,. (2016). Surface Analysis. Retrieved from http://www.wpc.ncep.noaa.gov/html/sfc2.shtml

Seidel, T., Weihrauch, D., Kimball, K., Pszenny, A., Soboleski, R., Crete, E., & Murray, G. (2009). Evidence of Climate Change Declines with Elevation Based on Temperature and Snow Records from 1930s to 2006 on MW, New Hampshire, U.S.A. Arctic, Antarctic, And Alpine Research, 41(3), 362-372.

American Meteorological Society. (2012). "free atmosphere". Glossary of Meteorology. [Available online at http:// http://glossary.ametsoc.org/wiki/Free_atmosphere].

Hoskins, B. & Ambrizzi, T. (1993). Rossby Wave Propagation on a Realistic Longitudinally Varying Flow. Journal Of The Atmospheric Sciences, 50(12), 1661-1671.

Jet Streaks: wind speed maxima within the jet stream. (1999). Ww2010.atmos.uiuc.edu. Retrieved 19 February 2017, from http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/cyc/upa/jetstrk.rxml

Sun, W. & Sun, O. (2015). Bernoulli equation and flow over a mountain. Geoscience Letters, 2(1).

Barry, R. (2013). Mountain Weather and Climate (1st ed.). Routledge.

Singleton, T. (2017). MW Statistical Tests, 2016-2017 [Excel Spreadsheet]. University of Portsmouth.

Oke, T. (1987). Boundary layer climates (1st ed.). London: Taylor & Francis.

Cermak, J. (1976). Aerodynamics of Buildings. Annual Review Of Fluid Mechanics, 8(1), 75-106.

Kaspi, Y. & Schneider, T. (2011). Winter cold of eastern continental boundaries induced by warm ocean waters. Nature, 471(7340), 621-624.

Influence of Rossby wave-breaking on the North Atlantic Oscillation. - RECYF Recherche et EXpérimentation sur les CYclogénèses et les Fronts. (2017). Umr-cnrm.fr. Retrieved 20 February 2017, from http://www.umr-cnrm.fr/recyf/spip.php?article14&lang=fr

Mount Washington Observatory | Research & Product Testing | Mount Washington Observatory. (2017). Mountwashington.org. Retrieved 20 February 2017, from https://www.mountwashington.org/research-and-product-testing/

Henson, R. & Anatta,. (1999). Mt. Washington's wild weather sheds light on aircraft icing. UCAR Quarterly, Summer 1999(24), 1-2.

Hiemstra, C., Liston, G., & Reiners, W. (2002). Snow Redistribution by Wind and Interactions with Vegetation at Upper Treeline in the Medicine Bow Mountains, Wyoming, U.S.A. Arctic, Antarctic, And Alpine Research, 34(3), 262.

Marks, D. & Winstral, A. (2001). Comparison of Snow Deposition, the Snow Cover Energy Balance, and Snowmelt at Two Sites in a Semiarid Mountain Basin. Journal Of Hydrometeorology, 2(3), 213-227.

Kullman, L. (2010). Wind-Conditioned 20th Century Decline of Birch Treeline Vegetation in the Swedish Scandes. *ARCTIC*, *58*(3).

Poulos, G. & Zhong, S. (2008). An Observational History of Small-Scale Katabatic Winds in Mid-Latitudes. Geography Compass, 2(6), 1798-1821.